Experiment and simulation analysis on high-speed up-film transplanting mechanism

Jin Xin[1], Pang Jing[1], Ji Jiangtao[1*], Du Xinwu[1], He Zhitao[1], Wang Shiguang[2]

(1. *College of Agricultural Equipment Engineering, Henan University of Science and Technology, Luoyang 471003, China*;
2. *Chinese Academy of Agricultural Mechanization Sciences, Beijing 100083, China*)

Abstract: Planting mechanism is a key component on transplanter to plant pot seedlings into soil. It is aimed at planting seedlings stably at high speed, and rising up quickly without taking out any seedlings. In order to adapt to transplanting with mulch film, the film should be perforated and the planting mechanism should ascend quickly to avoid film tearing. In this paper, an analysis on the ideal movement trajectory of pot seedlings and planting mechanism during the high-speed planting process was made, and a seven-rod planting mechanism was proposed, and also a 3D simulation model of the mechanism is established. Transmission ratio, length of the two cranks, phase difference of the cranks, angle of planting mouth were adopted as the test factors; trajectory characteristics were selected as assessment indexes in this study, and an orthogonal simulation test of factor effects was done and the influence rule of key parameter changes of planting mechanism on planting trajectory was found out, the following optimized parameter combination was obtained: L_1=30 mm, L_2=184 mm, L_3=34 mm, L_4=110 mm, L_5=13 mm, L_6=146 mm, L_7=71 mm, L_8=64 mm, L_9=240 mm, L_{10}=255 mm; φ_1=70°, φ_3=229°, β=86°, γ=93°, $\omega=\pi$ rad/s, v_x=500 mm/s. When the planting frequency was 70/min, the penetration depth of the planter was 50 mm; and the lengths of approximate straight-line segments of the planting trajectory in earth and elevating trajectory were 76 mm; and the hole size was a bit bigger than that of the penetration unit. Field experiment results show that: when advancing velocity was 0.57 m/s, transplanting efficiency was 66/min, perpendicularity of the seedlings was 93.6%, seedling leakage rate was 6.8%; qualification rate of row spacing was 100%, showing that the condition could meet the requirement of high-speed up-film transplanting.

Keywords: up-film transplanting, planting mechanism, simulation analysis, orthogonal test

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1 Introduction

During the transplanting process, the unit that plant single pot seedling into the soil is called planting mechanism, and the ground-breaking planting method widely utilized at present applies the method of ditching (He, 2014; Hu, 2011). Plastic film mulching has significant advantages in heat preservation, moisture preservation, nutrition maintenance, lighting effect increasing and prevention of disease, insect and weed, besides, it can achieve precocity and yield increase. With the application of plastic film mulching technology, there are new demands on the penetration method of transplanter's planting mechanism (Wang et al., 2015; Feng et al., 2002). At present, the planting mechanisms suitable for up-film transplanting are planetary rotary arm type, parallelogram type, multi-link type, turbine type, dibble type and duckbilled type (Zhang et al., 2011; Zhou et al., 2003). These devices may tear film or take away seedlings at high working speed because of restrictions in planting trajectory; therefore, the planting efficiency and quality may be reduced. For this reason, the planting mechanisms stated above are not applied in large-scale promotion.

The moving trajectory of parallelogram planting mechanism with duckbilled planting device may have curtate cycloid, cycloid and trochoid influenced by characteristic parameter λ. A study showed that, λ>1 is the

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* **Corresponding author: Ji Jiangtao,** Professor, College of Agricultural Equipment Engineering, Henan University of Science and Technology, Luoyang 471003, China. Email: jjt0907@163.com.

necessary condition for normal working of the planting mechanism; when $\lambda>1$, the moving trajectory of the duckbilled planting device may form the shape of a retaining ring (Chen et al., 2013), thus can meet the necessary conditions of the parallelogram planting mechanism, but in the same time increase the stir of soil and enlarge the size of the hole made by the duckbilled device.

The main working units of turbine type planting mechanism are turbine and spades, which are evenly distributed on the outershell of the turbine. It works by rolling the tractor-driven turbine through friction with the soil; in the meantime, the spades on the tip circle penetrate into the film and perforate on the soil (Jin et al., 2016). The moving trajectory of the spades is trochoid, and the trajectory doesn't have approximate straight-line segments with that of the penetration and moving up process required by up-film transplanting.

The planetary rotary-arm type planting mechanism is mainly composed of planet wheel, planet carrier and planting device (Liu et al., 2017). Compared with connecting rod mechanism, it can plant seedlings with stability at high speed, but the trajectory of planting device doesn't have any perpendicular stage during the penetration and moving up process, so the hole may be enlarged and seedlings may be easily taken out.

The multi-link planting mechanism uses the combination of cranks and connecting rods to realize the trajectory of planting device. It has the advantages of simple structure and diversified trajectories (Chen et al., 2011; Jin et al., 2012). By learning from the research results on theory of mechanism, a seven-rod planting mechanism based on the ideal moving trajectory of up-film high speed transplanting and planting device was designed in this paper, and the modeling, simulation and test analysis on the mechanism was done, the influence rule of key parameters on trajectory was found out, and finally the optimal parameter combination was obtained. The penetration and moving up trajectories of the planting point were almost perpendicular and the there were a long part of trajectory overlapping straight-line segment.

2 Analysis on the process of up-film planting

2.1 Analysis on the moving trajectory of pot seedlings

The movement of pot seedlings can be divided into two stages: seedling dropping and seedling planting.

(1) Seedling dropping is the moving process of pot seedlings from the dropping drum to reaching the planting device. Suppose that the initial speed of pot seedlings at upright direction is zero, the main forces on the seedlings are gravity and air resistance.

Thus, the force on pot seedlings at upright direction is:

$$F=mg-ksv_y \tag{1}$$

where, m is the mass of pot seedling; g is gravity acceleration; k is air resistance coefficient, which is generally 2.937(Li et al., 2012; Wang et al., 2009); s is the area of resistance at upright direction, namely, the frontal projected area of seedling leaves; v_y is the instantaneous speed of seedling at upright direction at time point t.

The speed of pot seedling at upright direction during seedling dropping is:

$$v_y=(g-ksv_y/m)\cdot t \tag{2}$$

Displacement of pot seedling at upright direction during seedling dropping is:

$$S_y=\int_0^t (g-ksv_y/m)tdt \tag{3}$$

The displacement of pot seedling at horizontal direction during seedling dropping is:

$$S_x=v_x t-\int_0^t (v_x-ks_1 v_x/mt)dt \tag{4}$$

where, v_x is the advancing velocity of the machine; s_1 is the area of resistance of pot seedling at advancing direction, namely, the projected area of seedling leaves at advancing direction.

(2) Seedling planting is the process from the touching point between pot seedling and the planting device to the lowest point of the planting device.

In the moving process of the pot seedlings and planting device, the ideal moving trajectory of pot seedlings is the perpendicular line to the ground, namely, the absolute speed of pot seedling at advancing direction is zero, and the ideal moving trajectory of pot seedling in planting is shown in Figure 1.

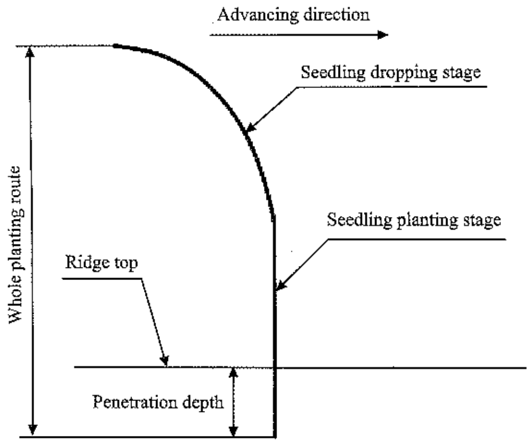


Figure 1 Ideal moving trajectory of pot seedling planting

2.2 Moving trajectory of the duckbilled planting device

The planting device first catches the dropped pot seedling and perforates on the film, then plants the seedling into soil. The trajectory of the duckbilled planting device from the lowest point to seedling catching point next time can be divided into two sections. To avoid the influence on the perpendicularity of pot seedlings and reduce horizontal film break, there should be a vertical lifting section for the duckbilled planting device; and the section ends when the lowest point of duckbilled planting device reaches the top of the pot seedlings; there is a free lifting section from the end of vertical lifting to the point of catching the next seedling, and this section doesn't have any strict demands on the trajectory of duckbilled planting device, except that it should keep upright when it reaches the point of catching the next seedling and keep the speed and acceleration as low as possible.

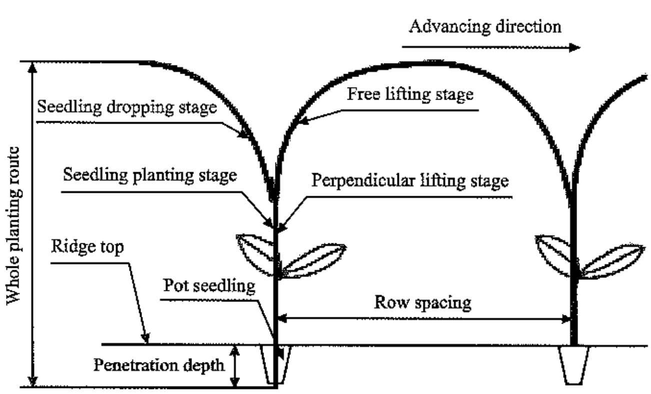


Figure 2 Ideal moving trajectory of the planting device

The analysis above can divide the moving trajectory of duckbilled planting device into four stages (as is shown in Figure 2): seedling dropping, planting, perpendicular lifting and free lifting. When the stages of planting and perpendicular lifting overlap each other, better planting effects can be achieved with the minimum degree of film break. At the top of the trajectory, there should be a relatively even section, which is good for catch seedlings steadily.

3 Simulation and modeling of planting mechanism

The planting mechanism is a double-crank seven-rod mechanism, whose movement is shown in Figure 3. Crank *AB* and crank *CD* are the two driving links with the same rotation direction and the same rotary speed. Rod *BG* and crank *AB* are hinged at point *B*, rod *DF* and rod *EF* are hinged at point *F*, rod *BG* and rod *EF* are fixed at point *E* and *EF* is perpendicular to *BG*, rocking bar *LI* and body frame are hinged at point *L*, and rod *GI* is hinged with rod *BG* and rocking bar *LI* at points *G* and *I* respectively. The duckbilled planting device is simplified as rod *JK*, and point *K* is the planting point of the device (namely the end point), *JK* is fixed on the rod *GI* through rod *HJ* (*H* is the midpoint of *GI* and *HJ* is perpendicular to *GI*). When the machine advances forward, the driving force is transmitted through gearbox to the cranks *AB* and *CD* of the seven-rod planting device, and the multi-link drives the duckbilled planting device to catch and plant seedlings.

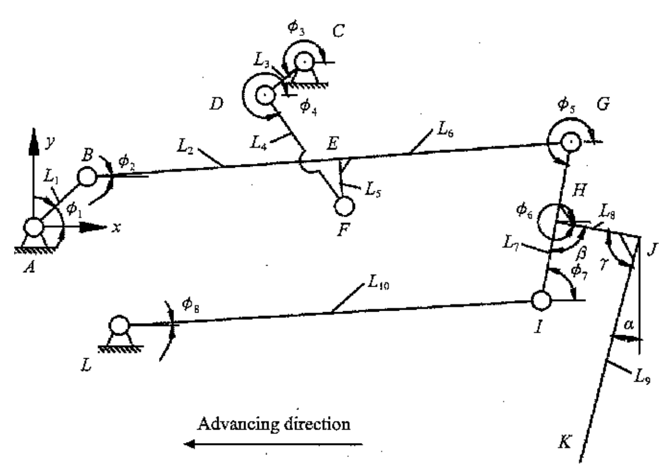


Figure 3 Motion diagram of the seven-rod planting mechanism

Where, L_i (i=1, 2 …, 10) is rod length, mm; φ_i (i=1, 2 …, 8) is the starting phase angle of the corresponding rod, (°); α is the initial angle of the duckbilled planting device, (°); ω represents the angular velocity of the two cranks, rad/s; γ represents the angle between the central axis of the duckbilled planting device and the fixed rod HJ, (°).

Based on the motion diagram, the software ADAMS-2013 was used for virtual modeling of motion, as is shown in Figure 4. In the figure, the hinge points of each rod are revolving pairs, which hinge rods *AB*, *CD* and *LI* together on the body frame. The body frame and the ground are combined by moving pairs. Then render rod AB and rod CD with rotational speed by the order of rotational joint motion, and render the body frame with translational speed by the point motion order.

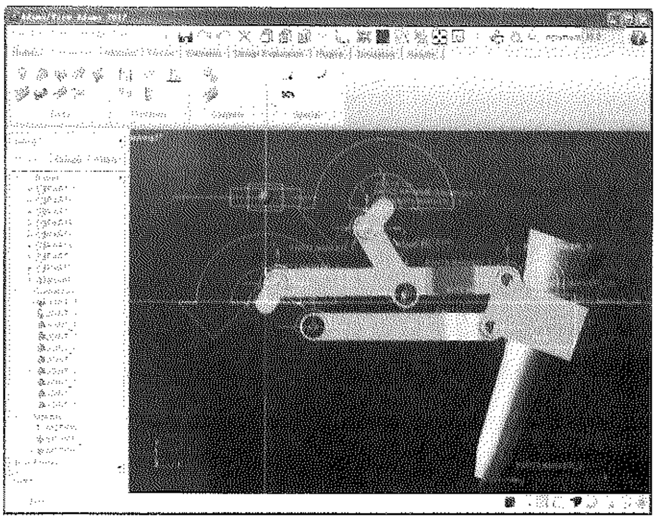


Figure 4 Simulation model of the seven-rod planting mechanism

4 Simulation test analysis of the planting mechanism

4.1 Test factors and evaluation indices

The motion diagram of the planting mechanism shows that, the lengths of crank *AB* and crank *CD* determine the swing scope of the machine at the advancing direction and height of moving trajectory of the duckbilled planting device; the phase difference of the two cranks φ_{AC} may influence the speed matching of motion at vertical and horizontal directions and then influence the shape of the trajectory; the initial angle α of the duckbilled planting device determines its penetration posture and seedling picking status; therefore, L_1, length of crank *AB*, and L_3, length of crank *CD*, phase difference of the two cranks φ_{AC} and initial angle of the duckbilled planting device α were selected as the influencing factors on planting trajectory for the simulation test analysis.

Taking trajectory characteristics as evaluation factors, the trajectory characteristics of up-film planting mechanism are the overall height of the trajectory, height difference between the overlapping vertical section and the trajectory of seeding catching stage. Trajectory evaluation parameters $\sum\Delta H$ was introduced and the following equation can be obtained:

$$\sum\Delta H=\Delta H_1+\Delta H_2+\Delta H_3 \tag{5}$$

where, ΔH_1 is the absolute difference between overall height of the trajectory and the standard value of trajectory height, mm; ΔH_2 is the absolute difference between height of the vertical section and standard value of the vertical section, mm; ΔH_3 is the absolute difference between the height of trajectory in seedling catching and the standard value of the height of trajectory in seedling catching, mm.

4.2 Orthogonal experiment

Four-factor and three-level virtual orthogonal experiment was adopted and the factor level coding is shown in Table 1.

Table 1 Coding of factors and levels

Levels	Factors			
	L_1, mm	L_3, mm	φ_{AC}, (°)	α, (°)
1	27	28	159	15
2	30	31	169	20
3	33	34	179	25

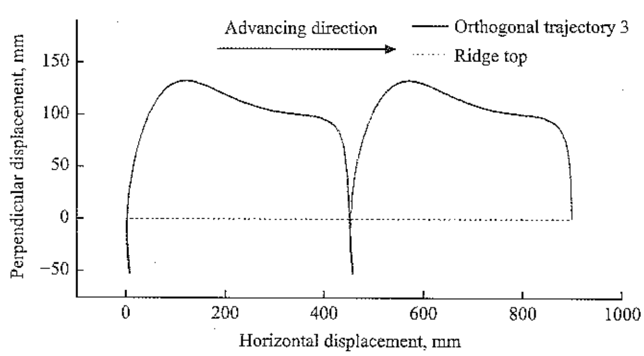
The orthogonal experiment and the results are shown in Table 2. The overall height is the gage length from the lowest point to the highest point of the trajectory; the height of the vertical section is the trajectory length of the stage when the distance of penetration and moving up trajectory of duckbilled planting device is less than 10 mm; height difference of seedling catching stage is the part above the height of the seedling.

The trajectory curve of some test points is shown in Figure 5.

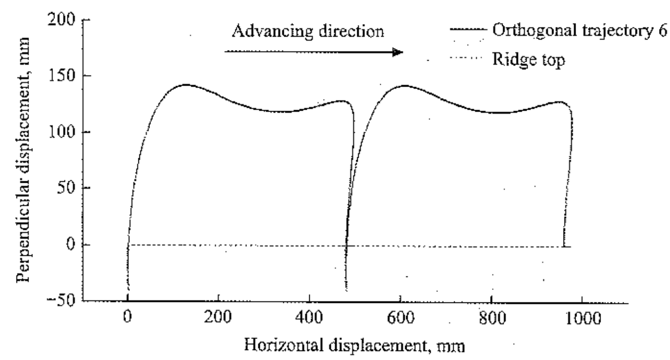
The height of seedling pots was among 30-40 mm, therefore, the penetration depth should be more than 50 mm; the seedling height was among 100−120 mm, so the highest point of the planting trajectory should be 120 mm higher than the ridge top. Since the total height of pot seedlings was lower than 160 mm, the height of planting trajectory should be a little bit higher, and 170 mm was an ideal height; since seedling height was 160 mm, the trajectory height at vertical direction should be higher than 160 mm; duckbilled planting device should catch the seedlings at the same height, therefore, the height difference of trajectory at seedling catching stage was almost zero. The smaller the trajectory evaluation parameter is, the more approximate was the trajectory to the ideal trajectory.

Table 2 Orthogonal experiment scheme and result

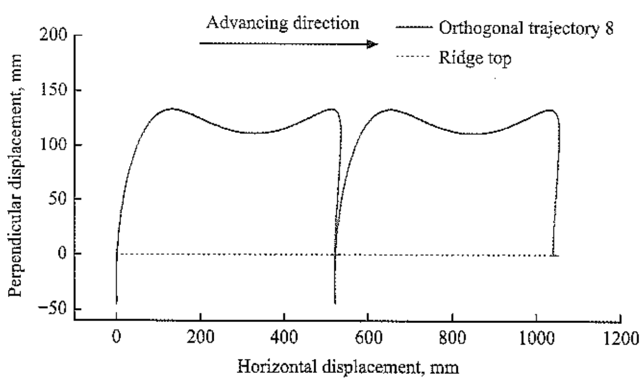
Test No.	Factors				Overall height of trajectory, mm	Characteristic parameters of the trajectory and height of perpendicular overlapping section, mm	Height difference of seedling catching stage, mm	Evaluation parameters of the trajectory, mm
	L_1, mm	L_3, mm	φ_{AC}, (°)	α, (°)				
1	1	1	1	1	146	60	15	139
2	1	2	2	2	169	69	26	118
3	1	3	3	3	185	70	41	146
4	2	1	2	3	163	60	15	122
5	2	2	3	1	211	88	83	196
6	2	3	1	2	184	115	19	78
7	3	1	3	2	207	90	80	187
8	3	2	1	3	180	85	21	106
9	3	3	2	1	236	115	87	198



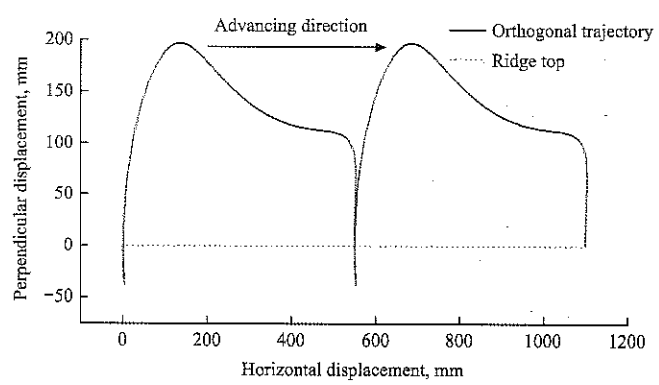
a. Test point 3



b. Test point 6



c. Test point 8



d. Test point 9

Figure 5 Planting trajectory curve in the orthogonal test

Test result showed that trajectory evaluation parameter of the simulation test point 6 was the minimum; the planting trajectory was the most similar to ideal trajectory. The comparatively better parameter combination is: L_1= 30 mm, L_2=184mm, L_3=34 mm, L_4=110 mm, L_5=13 mm, L_6=146 mm, L_7=71 mm, L_8=64 mm, L_9=240 mm, L_{10}= 255 mm; φ_1=70°, φ_2=1°, φ_3=229°, φ_4=300°, φ_5=251°, φ_6=338°, φ_7=71°, φ_8=3°, α=20°.

4.3 Discussion

When the planting frequency was 60/min, the static trajectory, the speed at vertical direction and hole size under optimal parameter combination are shown in Figures 6 to 8.

Figure 6 shows that, the width of the static trajectory is 180 mm, the top of the trajectory is relatively smooth and even and good for catching seedlings.

Figure 7 shows that, the speed of the duckbilled planting device at vertical direction is among the range of 0.9-0.75 m/s. When the initial speed of the duckbilled planting device in penetration was 0.75 m/s, and the speed at vertical direction reduced sharply to let pot seedlings drop to the bottom of the duckbilled planting device. In this way, the pot seedlings can be easily planted into soil when the duckbilled planting device reached the lowest point.

Figure 8 shows that, the hole made by the nozzle is a little bit larger than the nozzle itself, thus it can effectively reduce damages on mulching film.

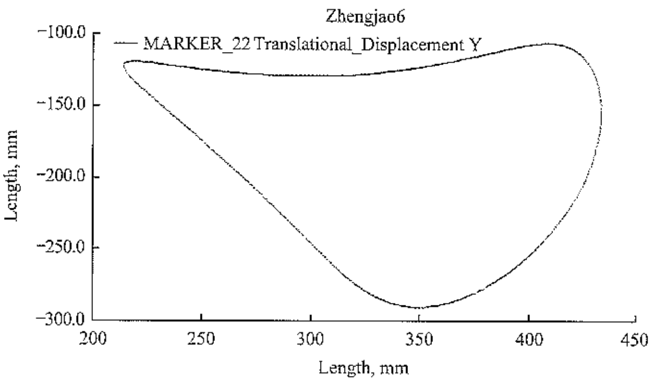


Figure 6 Static trajectory curve of the duckbilled planting device

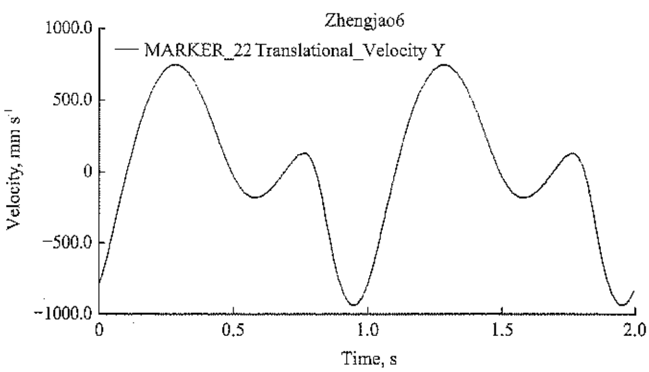


Figure 7 Speed curve of the duckbilled planting device at vertical direction

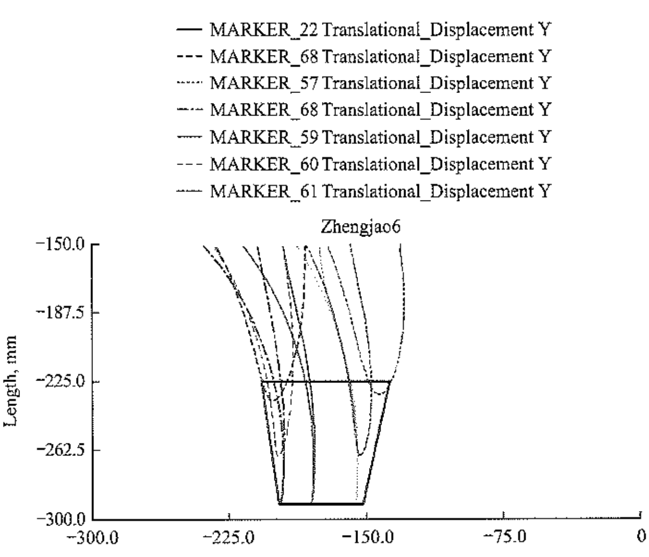


Figure 8 Hole size

5 Field test

5.1 Test conditions

Test materials: tobacco pot seedlings were selected as planting objects in the test. The seedling age was about 40 days; the seedling cultivation substrate was made up of peat, perlite and vermiculite, whose volume ratio was 3:1:1; the substrate was in a cone shape, with diameter of 10 mm at the bottom and diameter of 20 mm at the top, height of 40 mm. The average height of pot seedlings was 151.6 mm, average width of seedling leaf was 99.2 mm. 150 pot seedlings were prepared in the test.

Test equipment: a sample transplanter with a seven-rod planting mechanism (Figure 9); a tape with measuring range of 100 m, a vernier caliper with precision of 0.01 mm, a timer and a protractor.

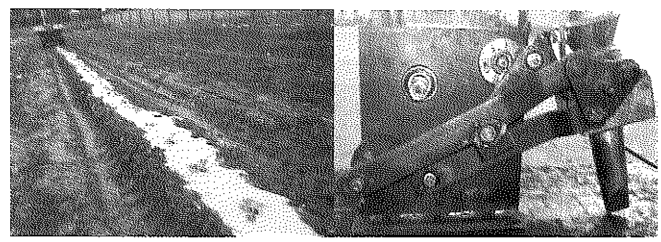


Figure 9 Test of the seven-rod planting mechanism

5.2 Evaluation indices

(1) Seedling perpendicularity

Seedling perpendicularity refers to the standing status of seedlings after transplanting, which is represented by α, the angle between seedling stalk and the ground. The standing status of seedling can be defined as: $\alpha \leq 45°$ is lodging status, $\alpha > 45°$ is qualified status, and $\alpha \geq 70°$ is excellent standing status.

Lodging rate: $F=A_1/M\times 100\%$

Qualification rate of perpendicularity: $H=A_2/M\times 100\%$

Excellence rate of perpendicularity: $Y=A_3/M\times 100\%$

where, A_1 is number of lodged seedlings; A_2 is number of seedlings in qualified status; A_3 is number of seedlings in excellent status; M is total number of seedlings.

(2) Seedling exposure rate

Seedling exposure refers to the status of planted seedlings with insufficient covering soil, when the root system or pot is totally exposed on soil.

Seedling exposure rate: $L=A_4/M\times 100\%$

where, A_4 is number of exposed seedlings; M is total number of measured seedlings

(3) Qualification rate of row spacing

Qualification rate of row spacing is an important index that indicates planting uniformity. Qualified seedling distance can be defined as:

$$0.5Xr<Xi\leq 1.5Xr$$

where, Xi is measured seedling distance; Xr is rated seedling distance

5.3 Test method

A transplanter with a seven-rod planting mechanism dragged by a Dongfanghong 300 tractor was used for transplanting in the test. The test area was 50 m, and preparation area was 15 m; the transplanting effects of tobacco pot seedling were tested when the tractor was set at second gear (0.375 m/s), third gear (0.577 m/s) and fourth gear (0.789 m/s) respectively. The test site and seven-rod planting device are shown in Figure 9.

5.4 Results and analysis

After film-covering and ridge-forming, three groups of field transplanting tests were conducted, and the test results are shown in Table 3.

Table 3 Test results

Traction gear	Measured advancing velocity, m/s	Planting efficiency, seedling, min	Perpendicularity qualification rate, %	Seedling exposure rate, %	Qualification rate of row spacing, %
Second gear	0.36	42	100	0	100
Third gear	0.57	66	93.6	6.8	100
Fourth gear	0.75	87	83.4	23.5	100

The results of field transplanting test show that, under traction speed of the second and third gear of the tractor, the seven-rod transplanting mechanism had the qualification rate of perpendicularity of over 90% with low seedling exposure rate and good working performance; under the traction speed of the fourth gear, more lodged seedlings were caused, and the qualification rate of perpendicularity reduced to 83.4%, and could not satisfy the agronomic requirements of transplanting (≥90%). Therefore, when the advancing speed was around 0.57 m/s, namely when planting frequency was 66 seedlings/min, the seven-rod planting mechanism can accomplish the high-speed up-film transplanting work.

6 Conclusions

(1) The seven-rod planting mechanism was proposed and a 3D simulation model of the mechanism was established. The orthogonal simulation test obtained a better combination of key parameters for the planting mechanism: when the planting frequency was 70/min, the penetration depth of the planter was 50 mm, and the length of similar straight-line segment of the planting trajectory in earth and elevating trajectory was 76 mm, the hole size was similar to that of the penetration unit.

(2) Field experiment results of the seven-rod planting mechanism show that: when advancing velocity was 0.57 m/s, transplanting efficiency was 66/min, qualification rate of upright pot seedlings was 93.6%, seedling leakage rate was 6.8%, qualification rate of row spacing was 100%, showing that the condition could meet the requirement of high-speed up-film transplanting.

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