# Experiment and parameter optimization of an automatic row following system for the traction beet combine harvester

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**Abstract:** To improve the automation level and operation quality of China's beet harvester and reduce the loss due to damaged and missed excavation, this study used a self-developed sugar beet combine harvester and field simulation experiment platform, based on the single-factor bench test of the automatic row following system in the early stage, taking hydraulic flow *A*, spring preload *B*, and forward speed *C* which have significant influence on performance indices as test factors, and taking the missed excavation rate, breakage rate and reaction time as performance indices, the orthogonal experimental study on the parameter optimization of the three-factor and three-level automatic row following system with the first-order interaction of various factors was carried out. The results of the orthogonal experiments were analyzed using range analysis and variance analysis. The results showed that there were differences in the influence degree, factor priority order and first-order interaction, and the optimal parameter combination on each performance index. A weighted comprehensive scoring method was used to optimize and analyze each index. The optimal parameter combination of the overall operating performance of the automatic row following system was $A_2B_2C_1$, that is, the hydraulic flow was 25 L/min, the forward speed was 0.8 m/s, and the spring preload was 198 N. Under this combination, the response time was 0.496 s, the missed excavation rate was 2.35%, the breakage rate was 3.65%, and the operation quality was relatively good, which can meet the harvest requirements. The comprehensive optimization results were verified by field experiments with different ridge shapes and different planting patterns. The results showed that the mean values of the missed excavation rate of different planting patterns of conventional straight ridges and extremely large "S" ridges were 2.23% and 2.69%, respectively, and the maximum values were 2.39% and 2.98%, respectively; the average damage rates were 3.38% and 4.14%, and the maximum values were 3.58% and 4.48%, which meet the industry standards of sugar beet harvester operation quality. The overall adaptability of the automatic row following system is good. This study can provide a reference for research on automatic row following harvesting systems of sugar beets and other subsoil crop harvesters.

**Keywords:** beet, combine harvester, traction type, parameter optimization, automatic row following
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## 1 Introduction

Sugar beets, the second largest raw material for sugar production in China, are mainly distributed in Xinjiang, Heilongjiang, Inner Mongolia, Jilin, Gansu, Ningxia, Liaoning, and other provinces in China. In 2019, the planting area of sugar beet in China reached $2.23\times10^5$ hm$^2$, and the output reached $1.23\times10^5$ t, which is increasing year by year. However, the mechanization level of beet harvesting in China is low, and it is still dominated by manual and semimechanized methods, which has become the main "bottleneck" in the development of the industry[1-3]. Therefore, improving the mechanized production level of sugar beets is of great significance to ensure the safety of the sugar supply in China.

The main sugar beet-producing areas in China mostly adopt the production method of single ridge-single row ridge cropping and transplanting. However, due to the lack of transplanting technical specifications and standards and the uncertainty of varieties, regions, and field conditions, there are prominent problems such as unequal row spacing, large differences in geometric shapes, uncertain distribution airspace (spatial areas distributed in the up and down, left and right, front and rear directions) and poor linear distribution on ridges. During excavation and harvesting operations, if there is a deviation in the forward direction of the shovel, it will cause missed excavation, less excavation, or root damage, requiring manual excavation again, which will result in large losses and low efficiency. At the same time, in order to reduce losses, the driver needs to pay close attention to the harvest row, adjusting the forward direction in real-time leading to high labor intensity. The operation performance is easily affected by

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human factors, so it is difficult to ensure the harvest operation's effect and efficiency. Therefore, it is necessary to carry out precise alignment and correction operations during the combined harvesting of sugar beets.

Overseas research on the mechanization of beet harvesting technology is relatively early, Marchant et al.[4] developed an automatic depth-limiting steering system for a traction-type sugar beet harvester driving a hydraulic servo system through a pair of whisker rods riding on the sugar beet row. O'dogherty et al.[5] developed a geometric model of the beet top cutting mechanism and analyzed the factors affecting the inaccuracy of the crown top sensing by the top detection wheels. Bulgakov et al.[6] studied agronomic parameters such as the height distribution of the beet root crown protruding from the soil surface in order to avoid the loss caused by excessive cutting of the beet root crown and at the same time to avoid excessive stubble of the root crown, stem, and leaves. Prochazka[7] studied the effects of the circumferential speed, forward speed, and excavation depth of the driving wheel on the forces of the rotating excavation and lifting parts of sugar beets under different soil conditions. Bulgakov et al.[8,9] studied the influence of vibration of tractor front mounted beet leaf harvester on operation quality, established the mathematical relationship between beet root crown shape and topping loss, and established the vibration nonlinear differential equation of topping mechanism in the longitudinal vertical plane. Billington[10] designed a rotary cylinder inclined rod top cutter to solve the waste problem caused by the inside of the crown above the horizontal cutting top plane of the sugar beet that is still usable but discarded. Ivanetz et al.[11] used the LS-DYNA software to conduct virtual tests on the excavation parts of the Belarus VHP NAS sugar beet harvester and simulated and analyzed the effects of soil type, the opening angle of the excavation shovel, and the forward speed on the excavation process. Ivancan et al.[12], combined with the analysis of field experiments, concluded that the most important factors affecting the top cutting quality of sugar beet combine harvesters are crop condition, topping mechanism structure, working speed, uniformity of row spacing, and height difference between two adjacent sugar beet crowns. Tillett et al.[13] developed a high-speed automatic guidance system for beet row weeding on the basis of research on grain row weeding. Tsukor et al.[14] developed and optimized a noncontact sensor control system for automatic row following and automatic depth limiting of sugar beet harvesters by using 3D TOF camera technology. Most of the above research are focused on the research and development of the topping mechanism and other components, and there is a lack of research on the performance and parameter optimization of the whole machine.

In China, beet harvesters have been developed for many years, and a number of related equipment and products have also been developed, but most of them are segmented with a low automation level[15-19]. In recent years, the authors and their team have proposed an active automatic row following the digging and harvesting method, developed a scientific prototype of a traction sugar beet combine harvester, and conducted preliminary research on the top cutting device, the conveying device, and the automatic row following system[20-24].

This study used a sugar beet combine harvester and field simulation experiment platform developed by the author in the early stage as the test platform and takes the missed excavation rate, breakage rate, and response time to measure the quality of automatic row following operation as the test indicators. The main influencing factors of each performance indicator and their influence law are tested and researched to improve the sensitivity and performance of automatic rows following harvesting.

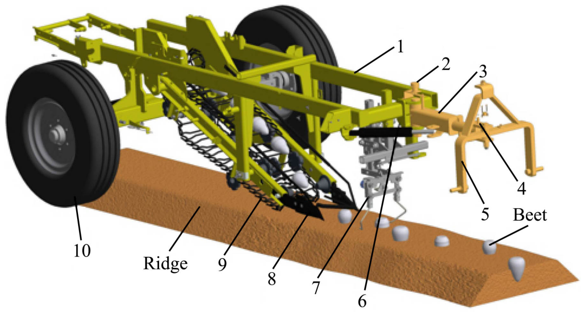
## 2 Structure and working principle of the sugar beet automatic row following harvesting test platform

### 2.1 Beet combine harvester

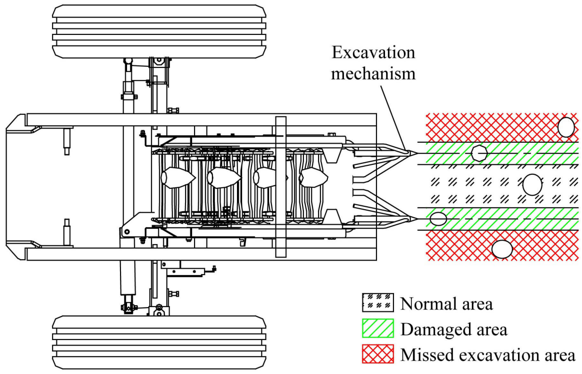
The beet combine harvester developed by Nanjing Institute of Agricultural Mechanization of the Ministry of Agriculture and Rural Areas is used. Its automatic row following device is mainly composed of a main frame, suspension mechanism, hydraulic deviation correction mechanism, deviation distance detection mechanism, excavation mechanism, and angle sensor, as shown in Figure 1a. The main parameters are listed in Table 1.

**Table 1 Major performance parameters**

| Items | Value |
|---|---|
| Row spacing/mm | 500-700 |
| Working width/mm | 1000-1400 |
| Number of work rows | 2 (1 row for leaf cutting and 1 row for excavation) |
| Excavation depth/mm | 0-180 |
| Working speed/m·s$^{-1}$ | 0.5-1.8 |




a. Schematic diagram of the automatic row following device structure



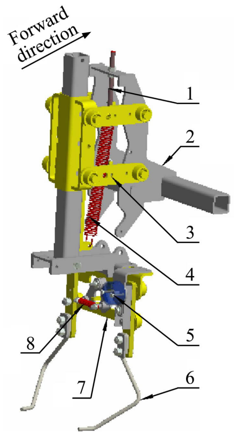

b. Schematic diagram of the automatic row following operation

1. Main frame 2. Rear angle sensor 3. Traction bar 4. Front angle sensor 5. Suspension mechanism 6. Hydraulic cylinder 7. Deviation distance detection mechanism 8. Excavation mechanism 9. Conveyor chain 10. Walking wheel

Figure 1 Schematic diagram of the structure and working principle of beet automatic row following combine harvester

During operation, deviation distance detection mechanism 7 detects the distance from the beet root to the row centerline and converts the information into an electrical signal, and transmits it to the controller. The controller outputs the hydraulic solenoid valve switch control signal based on the deviation distance to drive hydraulic cylinder 6 to expand and contract, driving traction rod 3 and main frame 1 to swing around the two hinge points of traction rod 3 and suspension mechanism 5 and main frame 1, and then drives the digging mechanism to swing left and right so that excavation mechanism 8 is aligned with the sugar beet roots for harvesting. At the same time, front and rear angle sensors 2 and 4, which are installed at the two hinge joints of traction rod 3, suspension mechanism 5, and main frame 1, monitor in real-time whether the automatic row following mechanism is corrected in place and back feed the information to the controller to form a closed-loop control system so that the forward path of the excavation mechanism is consistent with the distribution of beet roots on the ridge to realize automatic row following excavation and harvest. There are three main situations in the relative positions between the field beet root and the excavation mechanism, as shown in Figure 1b. When the combine harvester is operating, when the beet root is located in a normal area, it will be dug up intact; if it is located in a damaged area, it will lead to less excavation or breakage; if it is located in a missed excavation area, the missing excavation phenomenon will occur because it is beyond the excavation range of the excavation mechanism.

Among them, the deviation distance detection mechanism, one of the key components of the automatic row following device, is mainly composed of an up-down, left-right adjustment parallel four-bar mechanism, frame, tension spring, angle sensor, detection rod, return spring, etc., as shown in Figure 2. Tension spring 4 bears the weight of the whole deviation distance detection mechanism and adjusts the height of the deviation distance detection mechanism by adjusting bolt 1 according to the height of the ridge. At the same time, under the action of adjusting the parallel four-bar linkage up and down, the detection rod can float up and down based on the height of the ridge surface to achieve a profiling function. When the machine moves forward, the left and right detection rods 6 sense the left and right deviation of beet root on the ridge and drive the left and right adjustment parallel four-bar mechanism 7 to move horizontally. Angle sensor 5 installed on one of the fixed hinge shafts of the left and right adjustment parallel four-bar mechanism 7 converts the left and right displacement of detection rod 6 into an angle change, converts the angle change into a digital pulse signal, and transmits it to the controller. When detection rod 6 crosses the deviated beet roots, the left and right adjustment parallel four-bar linkage mechanism 7 returns to the normal position under the action of the return spring 8 and then drives detection rod 6 to return to the normal position.

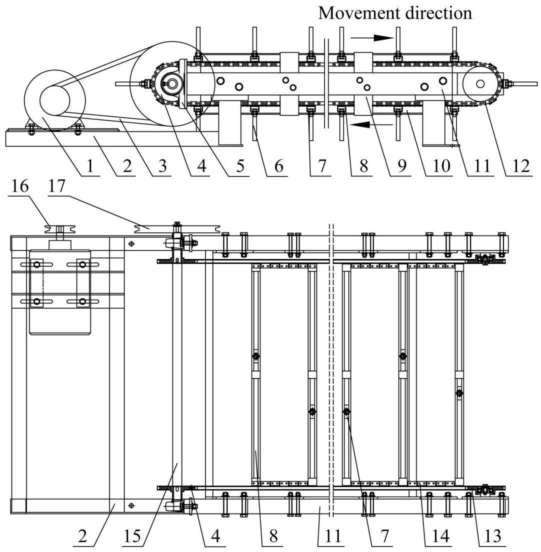



1. Adjusting bolt 2. Frame 3. Up and down adjusting parallel four-bar linkage 4. Tension spring 5. Angle sensor 6. Detection rod 7. Left and right adjusting parallel four-bar linkage 8. Return spring

Figure 2 Diagram of the detection mechanism

### 2.2 Field simulation of the experimental platform

The experimental platform developed by the Nanjing Institute of Agricultural Mechanization of the Ministry of Agriculture and Rural Affairs is used, which is mainly composed of the frame support device, plant spacing adjustment device, deviated row center distance adjustment device, operating speed adjustment device, transmission device, tensioning device and anti-drooping device of the transmission chain, as shown in Figure 3. It can simulate the planting agronomic parameters of sugar beets in the field, such as different plant spacings, different deviation distances from the centerline of the row, and different forward speeds of the harvester. The specific technical parameters are listed in Table 2.




1. Frequency conversion motor 2. Motor mounting frame 3. Belt 4. Driving sprocket 5. Bearing with seat 6. Beet mounting rod 7. Slider 8. Chute 9. Chain carrier mounting plate 10. Chain carrier box 11. Frame 12. Drive chain 13. Driven sprocket 14. Drive chain attached plate 15. Driving sprocket mounting shaft 16. Driving pulley 17. Driven pulley

Figure 3 Structure diagram of the field simulation test bench

**Table 2 Main technical parameters of the test bench**

| Items | Value |
|---|---|
| Electromotor | 1430 r/min, 0.55 kW |
| Frequency converter/kW | 0.75 |
| Off-centerline distance/cm | 0-35 |
| Plant spacing/cm | 2.5-80.0 |
| Forward speed/m·s$^{-1}$ | 0-2.08 |

## 3 Parameter optimization test

### 3.1 Test materials and instruments

Test materials: Sugar beets from Chahar Right Front Banner, Ulanqab City, Inner Mongolia Autonomous Region, China, one of the main sugar beet producing areas, were selected as the test material, and the variety was Jitian series.

Main instruments: TGT-100 type platform scale (range 100 kg, accuracy 0.02 kg), tape measure (range 5 m, accuracy 1 mm), Fluke 931 type tachometer (range 1-19 999 r/min, accuracy ±0.02%), Fluke 190-102 type oscilloscope (2 channels, bandwidth 100 MHz, vertical resolution 8 bit, a maximum real-time sampling rate of 1.25 GS/s, record length of 27 500 points per channel).

### 3.2 Test scheme design

According to the working principle, preliminary kinematics analysis, and single factor bench test analysis of the automatic row following system of the traction beet combine harvester, the performance indicators of the system, such as response time, missed excavation rate and breakage rate, are mainly affected by the spring preload, hydraulic flow, forward speed and deviation distance of the automatic row following system. All factors are within the following range: forward speed ($v$=0.4-2.0 m/s), hydraulic flow ($q$=15-35 L/min), spring preload ($F_y$=53-346 N), and deviation distance ($H$=3-15 cm), which have a significant impact on each performance indicator.

Therefore, taking the response time, missed excavation rate, and breakage rate as the test indicators, three factors that significantly affect the automatic row following indicator, i.e., forward speed $v$, hydraulic flow $q$, and spring preload $F_y$, are selected within an appropriate range to carry out a three-factor and three-level orthogonal test (the deviation distance in actual harvest is not a controllable factor, so it is omitted). It determines the primary and secondary factors affecting each indicator and the optimal parameter combination. The level of each factor is listed in Table 3. Considering the first-order interaction between each factor, an $L_{27}(3^{13})$ orthogonal table is selected for the orthogonal test[25-27]. Each test is repeated three times, and the test results are averaged.

**Table 3 Orthogonal test factors and levels**

| Level | Factors | | |
|---|---|---|---|
| | A<br>Hydraulic flow<br>$q$/L·min$^{-1}$ | B<br>Spring preload<br>$F_y$/N | C<br>Forward speed<br>$v$/m·s$^{-1}$ |
| 1 | 15 | 125 | 0.8 |
| 2 | 25 | 198 | 1.2 |
| 3 | 35 | 272 | 1.6 |

### 3.3 Test methods and indicators

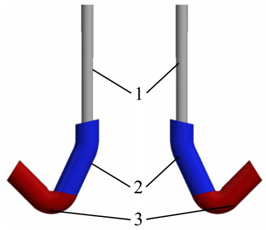
#### 3.3.1 Test method

The field simulation experiment platform is placed under the excavation mechanism and deviation signal detection mechanism of the sugar beet combine harvester, with power provided by a variable frequency motor; the sugar beet combine harvester is towed, hooked, and powered by a John Deere 1054 tractor that provides power, as shown in Figure 4.

Figure 4 Diagram of the harvester and test bench position

To avoid rigid contact and collision between the excavation mechanism and the block root mounting rod on the test bench, an elastic excavation mechanism is designed to replace the original rigid excavation mechanism, as shown in Figure 5. It is mainly composed of fixed rods and internal and external funnel-shaped elastic rods. The elastic excavation mechanism is connected to the excavator frame through a fixed rod. During the test, a high-speed camera was used for monitoring to calculate the missed excavation rate and breakage rate. When the beet root is in contact with the inner part of the elastic rod (the blue part in Figure 5), it indicates that the beet root is damaged. When it is in contact with the outer part (the red part in Figure 5), it indicates that the root is missing excavation. No contact with the inner and outer parts of the elastic rod means that this root is excavated normally.

To measure the response time of the automatic row following system, the sensor of the deviation signal detection system and the feedback sensor at the hydraulic deviation correction actuator are connected to the blue and red channels of the oscilloscope, respectively. The response time of the automatic alignment system is measured by grasping and analyzing the waveforms of the two sensors.




1. Fixed rod 2. Inner funnel-shaped part of elastic rod 3. Outer funnel-shaped part of elastic rod

Figure 5 Elastic excavation simulation mechanism

Spring preload adjustment method: Springs of the same stiffness are chosen to make springs with different lengths, and tension measurements are performed on the WDW-10 mechanical electronic universal testing machine to measure the actual tension of each spring when it is stretched to the installation length.

Forward speed adjustment method: The speed of the variable frequency motor is roughly adjusted through the frequency converter, and then the speed of the test bench is measured through the tachometer to calculate the accurate speed.

Hydraulic flow and pressure adjustment method: The hydraulic flow and pressure through the flow adjustment valve and overflow valve of the hydraulic system of the sugar beet combine harvester are adjusted.

Deviation distance and plant spacing adjustment method: The deviation distance of each beet root from the row center through the beet installation rod and slider of the field simulation experiment platform is adjusted. To facilitate the collection of test data, several consecutive beet roots were set at the same deviation distance. Different plant spacings were obtained by increasing or decreasing the number of chutes between two beet root installation rods.

#### 3.3.2 Test indicators

It can be seen from the above analysis that the harvest quality performance indicators related to the automatic row following of a sugar beet combine harvester mainly include the missed excavation rate, breakage rate, and sensitivity of the automatic row following system. Referring to "NY/T 1412-2007 Sugarbeet Harvester Operating Quality"[28], the test evaluation indicators are defined as follows:

1) Missed excavation rate

$$G_l = \frac{M_{lz}}{M} \times 100\% \quad (1)$$

where, $G_l$ is the missed excavation rate, %; $M_{lz}$ is the mass of missed roots, kg; $M$ is the total mass of test roots, kg; design requirements: $G_l \leq 3\%$.

2) Breakage rate

$$G_p = \frac{M_{pz}}{M} \times 100\% \quad (2)$$

where, $G_p$ is the breakage rate, %; $M_{pz}$ is the mass of damaged roots, kg; design requirements: $G_p \leq 4.5\%$.

3) Response time

It refers to the time required by the automatic row following system of the beet combine harvester from the detection of deviated beet roots to completing the deviation correction excavation. The response time reflects the sensitivity of the system, and the calculation formula is as follows:

$$T = T_1 + T_2 + T_3 \quad (3)$$

where, $T$ is the response time of the automatic row following system, s; $T_1$ is the signal extraction time of the deviation signal detection system, s; $T_2$ is the processing time of the signal processing control system, s; $T_3$ is the action time of the hydraulic deviation correction execution system, s; and the design requirement is $T \leq 0.65$ s.

### 3.4 Test results and analysis

The test plan and experimental data are listed in Table 4. The IBM SPSS Statistics 19 software was used for orthogonal test range analysis and variance analysis[29-31], and the test and range analysis results are listed in Table 4 and Table 5.

The range analysis results show that the primary and secondary orders of the influences of various factors on the system response time were spring preload ($B$), hydraulic flow ($A$), forward speed ($C$) and hydraulic flow×spring preload ($A\times B$), hydraulic flow×forward speed ($A\times C$), spring preload×forward speed ($B\times C$), and the optimal parameter combination was $A_2B_1C_3$, i.e. hydraulic flow $q$=25 L/min, spring preload $F_y$=125 N, forward speed $v$=1.6 m/s. The primary and secondary orders of the influences of various factors on the missed excavation rate were spring preload, hydraulic flow, forward speed and hydraulic flow×forward speed, hydraulic flow×spring preload, spring preload×forward speed, and the optimal parameter combination was $A_3B_3C_1$, i.e. hydraulic flow $q$=35 L/min, spring preload $F_y$=272 N, forward speed $v$=0.8 m/s. The primary and secondary order of the influence of various factors on the breakage rate is forward speed, hydraulic flow, spring preload, and hydraulic flow×spring preload, hydraulic flow×forward speed, spring preload×forward speed, and the optimal parameter combination is $A_2B_2C_1$, i.e., hydraulic flow $q$=25 L/min, spring preload $F_y$=198 N, forward speed $v$=0.8 m/s.

**Table 4 Test plan and experimental data**

| Test No. | Factors | | | | | | | | | Reaction time $T$/s | Missed excavation rate $G_l$/% | Breakage rate $G_p$/% | Comprehensive index $Z$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $A$ | $B$ | $A\times B$ | | $C$ | $A\times C$ | | $B\times C$ | | | | | |
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0.473 | 2.37 | 3.76 | 95.118 |
| 2 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 0.466 | 2.39 | 3.88 | 96.141 |
| 3 | 1 | 1 | 1 | 1 | 3 | 3 | 3 | 3 | 3 | 0.458 | 2.39 | 3.94 | 96.271 |
| 4 | 1 | 2 | 2 | 2 | 1 | 1 | 1 | 2 | 3 | 0.521 | 2.35 | 3.85 | 97.197 |
| 5 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 1 | 0.513 | 2.36 | 3.87 | 97.245 |
| 6 | 1 | 2 | 2 | 2 | 3 | 3 | 3 | 1 | 2 | 0.501 | 2.37 | 3.9 | 97.212 |
| 7 | 1 | 3 | 3 | 3 | 1 | 1 | 1 | 3 | 2 | 0.496 | 2.33 | 3.76 | 95.164 |
| 8 | 1 | 3 | 3 | 3 | 2 | 2 | 2 | 1 | 3 | 0.487 | 2.35 | 3.82 | 95.674 |
| 9 | 1 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 1 | 0.48 | 2.37 | 3.91 | 96.479 |
| 10 | 2 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 1 | 0.463 | 2.36 | 3.78 | 94.670 |
| 11 | 2 | 1 | 2 | 3 | 2 | 3 | 1 | 2 | 2 | 0.456 | 2.37 | 3.85 | 95.120 |
| 12 | 2 | 1 | 2 | 3 | 3 | 1 | 2 | 3 | 3 | 0.447 | 2.38 | 3.88 | 95.203 |
| 13 | 2 | 2 | 3 | 1 | 1 | 2 | 3 | 2 | 3 | 0.496 | 2.35 | 3.65 | 94.332 |
| 14 | 2 | 2 | 3 | 1 | 2 | 3 | 1 | 3 | 1 | 0.467 | 2.34 | 3.77 | 94.781 |
| 15 | 2 | 2 | 3 | 1 | 3 | 1 | 2 | 1 | 2 | 0.466 | 2.36 | 3.84 | 95.222 |
| 16 | 2 | 3 | 1 | 2 | 1 | 2 | 3 | 3 | 2 | 0.483 | 2.33 | 3.72 | 94.373 |
| 17 | 2 | 3 | 1 | 2 | 2 | 3 | 1 | 1 | 3 | 0.478 | 2.34 | 3.83 | 95.192 |
| 18 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 2 | 1 | 0.471 | 2.35 | 3.87 | 95.423 |
| 19 | 3 | 1 | 3 | 2 | 1 | 3 | 2 | 1 | 1 | 0.468 | 2.33 | 3.84 | 94.671 |
| 20 | 3 | 1 | 3 | 2 | 2 | 1 | 3 | 2 | 2 | 0.459 | 2.35 | 3.91 | 95.254 |
| 21 | 3 | 1 | 3 | 2 | 3 | 2 | 1 | 3 | 3 | 0.462 | 2.37 | 4.03 | 96.661 |
| 22 | 3 | 2 | 1 | 3 | 1 | 3 | 2 | 2 | 3 | 0.486 | 2.31 | 3.71 | 94.497 |
| 23 | 3 | 2 | 1 | 3 | 2 | 1 | 3 | 3 | 1 | 0.475 | 2.33 | 3.79 | 94.576 |
| 24 | 3 | 2 | 1 | 3 | 3 | 2 | 1 | 1 | 2 | 0.468 | 2.35 | 3.84 | 95.090 |
| 25 | 3 | 3 | 2 | 1 | 1 | 3 | 2 | 3 | 2 | 0.467 | 2.32 | 3.83 | 94.351 |
| 26 | 3 | 3 | 2 | 1 | 2 | 1 | 3 | 1 | 3 | 0.471 | 2.33 | 3.97 | 95.733 |
| 27 | 3 | 3 | 2 | 1 | 3 | 2 | 1 | 2 | 1 | 0.482 | 2.34 | 4.12 | 97.457 |

| Index | | $A$ | $B$ | $A\times B$ | | $C$ | $A\times C$ | | $B\times C$ | |
|---|---|---|---|---|---|---|---|---|---|---|
| Reaction time $T$ | $k_1$ | 0.488 | 0.461 | 0.473 | 0.472 | 0.484 | 0.475 | 0.478 | 0.475 | 0.477 |
| | $k_2$ | 0.470 | 0.488 | 0.480 | 0.484 | 0.475 | 0.480 | 0.475 | 0.480 | 0.474 |
| | $k_3$ | 0.471 | 0.479 | 0.476 | 0.473 | 0.471 | 0.473 | 0.476 | 0.474 | 0.478 |
| | Range | 0.018 | 0.027 | 0.007 | 0.012 | 0.013 | 0.007 | 0.004 | 0.005 | 0.005 |
| | Factor priority order | $B>A>C>AB>AC>BC$ | | | | Optimal combination | | $A_2B_1C_3$ | | |
| Missed excavation rate $G_l$ | $k_1$ | 2.364 | 2.368 | 2.351 | 2.354 | 2.339 | 2.350 | 2.351 | 2.351 | 2.350 |
| | $k_2$ | 2.353 | 2.347 | 2.353 | 2.350 | 2.351 | 2.356 | 2.350 | 2.353 | 2.352 |
| | $k_3$ | 2.337 | 2.340 | 2.350 | 2.350 | 2.364 | 2.349 | 2.353 | 2.350 | 2.352 |
| | Range | 0.027 | 0.028 | 0.003 | 0.004 | 0.026 | 0.007 | 0.003 | 0.003 | 0.002 |
| | Factor priority order | $B>A>C>AC>AB>BC$ | | | | Optimal combination | | $A_3B_3C_1$ | | |
| Breakage rate $G_p$ | $k_1$ | 3.854 | 3.874 | 3.816 | 3.862 | 3.767 | 3.848 | 3.868 | 3.842 | 3.857 |
| | $k_2$ | 3.799 | 3.802 | 3.894 | 3.869 | 3.854 | 3.857 | 3.838 | 3.861 | 3.837 |
| | $k_3$ | 3.893 | 3.870 | 3.837 | 3.816 | 3.926 | 3.842 | 3.841 | 3.843 | 3.853 |
| | Range | 0.094 | 0.072 | 0.079 | 0.053 | 0.159 | 0.014 | 0.030 | 0.019 | 0.020 |
| | Factor priority order | $C>A>B>AB>AC>BC$ | | | | Optimal combination | | $A_2B_2C_1$ | | |
| Comprehensive index $Z$ | $k_1$ | 96.28 | 95.46 | 95.19 | 95.49 | 94.93 | 95.43 | 95.75 | 95.40 | 95.60 |
| | $k_2$ | 94.92 | 94.57 | 96.02 | 95.91 | 95.52 | 95.74 | 95.38 | 95.77 | 95.33 |
| | $k_3$ | 95.37 | 95.54 | 95.36 | 95.16 | 96.11 | 95.40 | 95.43 | 95.40 | 95.64 |
| | Range | 1.35 | 0.97 | 0.83 | 0.75 | 1.18 | 0.34 | 0.37 | 0.37 | 0.31 |
| | Factor priority order | $A>C>B>AB>AC>BC$ | | | | Optimal combination | | $A_2B_2C_1$ | | |

**Table 5 Variance analysis of the spring preload on indices**

| | Sources | Sum of squares | df | Mean square | *F* value | *p* value |
|---|---|---|---|---|---|---|
| *T* | Correction model | 0.008[a] | 18 | 0.000 | 15.879 | 0.000 |
| | Intercept | 6.125 | 1 | 6.125 | 227482.256 | 0.000 |
| | *A* | 0.002 | 2 | 0.001 | 36.447 | 0.000 |
| | *B* | 0.003 | 2 | 0.002 | 62.403 | 0.000 |
| | *C* | 0.001 | 2 | 0.000 | 15.030 | 0.002 |
| | *AB* | 0.001 | 4 | 0.000 | 9.610 | 0.004 |
| | *AC* | 0.000 | 4 | 6.504E-5 | 2.415 | 0.134 |
| | *BC* | 0.000 | 4 | 6.709E-5 | 2.492 | 0.127 |
| | Error | 0.000 | 8 | 2.693E-5 | 0.000 | |
| | Sum | 6.133 | 27 | | | |
| $G_l$ | Correction model | 0.011[b] | 18 | 0.001 | 13.197 | 0.000 |
| | Intercept | 6.125 | 1 | 6.125 | 227482.256 | 0.000 |
| | *A* | 0.004 | 2 | 0.002 | 38.776 | 0.000 |
| | *B* | 0.004 | 2 | 0.002 | 41.714 | 0.000 |
| | *C* | 0.003 | 2 | 0.001 | 32.408 | 0.000 |
| | *AB* | 0.000 | 4 | 4.259E-5 | 0.939 | 0.489 |
| | *AC* | 0.000 | 4 | 7.037E-5 | 1.551 | 0.276 |
| | *BC* | 8.148E-5 | 4 | 2.037E-5 | 0.449 | 0.771 |
| | Error | 0.000 | 8 | 4.537E-5 | 0.000 | 8 |
| | Sum | 7 | 27 | | | |
| $G_p$ | Correction model | 0.201[c] | 18 | 0.013 | 10.157 | 0.001 |
| | Intercept | 149.296 | 1 | 149.296 | 3290569.000 | 0.000 |
| | *A* | 0.041 | 2 | 0.020 | 15.499 | 0.002 |
| | *B* | 0.029 | 2 | 0.015 | 11.270 | 0.005 |
| | *C* | 0.114 | 2 | 0.057 | 43.575 | 0.000 |
| | *AB* | 0.045 | 4 | 0.011 | 8.641 | 0.005 |
| | *AC* | 0.006 | 4 | 0.001 | 1.113 | 0.414 |
| | *BC* | 0.004 | 4 | 0.001 | 0.781 | 0.568 |
| | Error | 0.010 | 8 | 0.001 | | |
| | Sum | 400.226 | 27 | | | |

Note: a. $R^2 = 0.937$ (adjustment plan $R^2 = 0.912$); b. $R^2 = 0.967$ (adjustment plan $R^2 = 0.894$); c. $R^2 = 0.958$ (adjustment plan R square = 0.864).

The results of the variance analysis show that the factors have different influences on each performance indicator. At 95% confidence level, the hydraulic flow, spring preload, forward speed, and the interaction of hydraulic flow and spring preload have significant impacts on the system response time ($p<0.01$), and other factors are not significant ($p>0.05$). For the indicator of missed excavation rate, under the 95% confidence level, the influence of hydraulic flow, spring preload, and forward speed are all extremely significant ($p<0.01$), and the first-order interactions of various factors are not significant ($p>0.05$). Under the 95% confidence level, the hydraulic flow, spring preload, forward speed, and the interaction of hydraulic flow and spring preload have extremely significant effects on the breakage rate ($p<0.01$), and other interaction effects are not significant ($p>0.05$).

### 3.5 Comprehensive optimization of various indicators

From the above analysis of the test results, it can be seen that the primary and secondary order and significance of the impact of various factors and their first-order interaction on each performance indicator are different, and the optimal parameter combinations are also different. Therefore, the weighted comprehensive scoring method was used to optimize the test results to select the optimal parameter combination that makes each performance indicator as small as possible to achieve the best operation effect of the automatic row following system.

Since beets are mainly used to make sugar, in the actual excavation and harvesting process, missed excavation will cause waste and reduce farmers' income, however, damaged beets can still be sold for money. Therefore, considering the importance of the three performance indicators, 100 points are taken as the total "weight", the missed excavation rate accounts for 50 points, the breakage rate accounts for 30 points, and the response time accounts for 20 points. The calculation formula of the weighted comprehensive index *Z* is as follows:

$$Z_i = \sum_{j=i}^{27} W_j \frac{y_{ij}}{y_{j\max}} \tag{4}$$

where, $Z_i$ is the calculated value (weighted scoring index) obtained from test No. *i*, *i*=1, 2, 3, ..., 27; $W_j$ is the "weight" value of the *j*-th index, *j*=1, 2, 3, where $W_1$=50, $W_2$=30, $W_3$=20; $y_{ij}$ is the *j*-th index in test No. *i*, where $y_{i1}$ is the response time, $y_{i2}$ is the missed excavation rate, $y_{i3}$ is the breakage rate; $y_{i\max}$ is the maximum value of the *j*-th index in all 27 tests.

The results of the weighted comprehensive scoring index *Z* calculated by Equation (4) are listed in Table 4. Range analysis and variance analysis were performed on the comprehensive scoring test indicators, and the results are listed in Table 4 and Table 6, respectively.

**Table 6 Result of comprehensive score analysis variance**

| Sources | Sum of squares | df | Mean square | *F* | Sig. |
|---|---|---|---|---|---|
| Correction model | 25.111[a] | 18 | 1.395 | 13.461 | 0.000 |
| Intercept | 246262.03 | 1 | 246262.03 | 2376133.445 | 0.000 |
| *A* | 8.758 | 2 | 4.379 | 42.252 | 0.000 |
| *B* | 6.452 | 2 | 3.079 | 28.467 | 0.000 |
| *C* | 6.361 | 2 | 0.513 | 30.690 | 0.000 |
| *AB* | 1.942 | 4 | 0.458 | 5.843 | 0.041 |
| *AC* | 1.830 | 4 | 0.344 | 4.415 | 0.035 |
| *BC* | 1.374 | 4 | 0.104 | 3.315 | 0.070 |
| Error | 0.829 | 8 | | | |
| Sum | 246289.576 | 27 | | | |

It can be seen from Table 4 and Table 6 that various factors have different impacts on comprehensive index *Z*. With 95% confidence level, the factors hydraulic flow *A*, spring preload *B*, and forward speed *C* have extremely significant influences on the comprehensive index *Z* ($p<0.01$), the first-order interaction terms *AB* and *AC* have significant influences on the comprehensive index *Z* ($0.01<p<0.05$), and the interaction term *BC* has no significant influence on the comprehensive index ($p>0.05$). The primary and secondary order of factors that affecting the comprehensive index *Z* of the automatic row followed a descending order as *A*, *C*, *B*, *AB*, *AC*, and *BC*. Since the influence of factors *A*, *B*, and *C* on the comprehensive index *Z* is greater than their first-order interactions, the influence of the interaction can be ignored when selecting the optimal parameter combination. Finally, the optimal parameter combination of factors is determined as $A_2B_2C_1$, that is, the hydraulic flow rate is 25 L/min, the working forward speed is 0.8 m/s, and the spring preload is 198 N. Under the optimal parameter combination $A_2B_2C_1$, the response time of the automatic row following excavation and harvesting system is 0.496 s, the missed excavation rate is 2.35%, the breakage rate is 3.65%, and the weighted comprehensive index is 94.332%. The operation quality is relatively good, which can meet the harvesting requirements.

## 4 Field verification test

To test the optimization results of the bench test parameters and investigate the smoothness and adaptability of the automatic row following system, field tests were carried out at the experimental base of Jiangsu Academy of Agricultural Sciences.

Ridging and planting were carried out in advance, according to the planting mode in the main sugar beet-producing areas in China. The average row spacing was 600 mm, the ridge top width was 400 mm, and the ridge height was 85 mm. Two types of ridges were adopted in the experiment: a conventional straight ridge and an extremely large “S”-shaped ridge, as shown in Figure 6. There were four different planting patterns on each ridge, as shown in Table 7. At harvest time, the soil moisture content was 25.6%, and the hardness was 85.4 N/cm$^2$. During the test, the influencing factors were set as the abovementioned optimal parameter combination $A_2B_2C_1$, that is, the hydraulic flow rate was 25 L/min, the forward speed was 0.8 m/s, and the spring preload was 198 N. The length of each mode was 20 m, and the missed excavation rate and breakage rate (system response time) of each mode were calculated according to Equations (1) and (2). The test of each mode was repeated 3 times, and the average value was taken. The results are listed in Table 8.

a. Straight ridges b. Large “S” ridges c. Harvesting operations

Figure 6 Field test

**Table 7 Test cropping patterns**

| Planting pattern | | Plant spacing/cm | |
|---|---|---|---|
| | | 25 | 35 |
| Deviation distance/cm | 10 | W | X |
| | 15 | Y | E |

**Table 8 Field test results**

| Planting pattern | | Missed excavation rate $G_l$/% | | | | Breakage rate $G_p$/% | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Test 1 | Test 2 | Test 3 | Mean | Test 1 | Test 2 | Test 3 | Mean |
| Straight ridges | W | 2.04 | 2.27 | 2.32 | 2.21 | 3.56 | 3.44 | 3.74 | 3.58 |
| | X | 2.18 | 2.12 | 1.91 | 2.07 | 3.25 | 3.09 | 3.17 | 3.17 |
| | Y | 2.37 | 2.56 | 2.24 | 2.39 | 3.46 | 3.53 | 3.24 | 3.41 |
| | E | 2.21 | 2.18 | 2.33 | 2.24 | 3.21 | 3.57 | 3.33 | 3.37 |
| | Mean | 2.23 | | | | 3.38 | | | |
| Large “S” ridges | W | 2.45 | 2.52 | 2.38 | 2.45 | 3.73 | 3.84 | 3.95 | 3.84 |
| | X | 2.39 | 2.42 | 2.27 | 2.36 | 3.77 | 3.88 | 3.84 | 3.83 |
| | Y | 2.86 | 3.14 | 2.91 | 2.97 | 4.58 | 4.26 | 4.39 | 4.41 |
| | E | 3.02 | 3.18 | 2.74 | 2.98 | 4.37 | 4.63 | 4.44 | 4.48 |
| | Mean | 2.69 | | | | 4.14 | | | |

As seen from Table 8, the average value and maximum value of the missed excavation rate of different planting patterns on conventional straight ridges were 2.23% and 2.39%, respectively. The average breakage rate was 3.38%, and the maximum is 3.58%. The average value and maximum value of the missed excavation rate of different planting patterns on the extremely large “S”-shaped ridge were 2.69% and 2.98%, respectively. The average breakage rate was 4.14%, and the maximum was 4.48%. The average missed excavation rate and breakage rate of the two ridge shapes and four patterns are all within the design requirements of the performance indicators. The automatic row following system has good overall adaptability to different planting agronomies and meets the industrial standard for the operation quality of sugar beet harvesters (NY/T1412-2007).

It can also be seen from table 8 that on the extreme "S"-shaped ridge, when the beet roots deviate too far, the missed excavation rate and damage rate are close to the maximum value required by the performance indicators, and sometimes even exceed the range required by the indicators. The automatic row following system of the traction sugar beet combine harvester developed in this paper has relatively poor adaptability when the ridge shape is irregular and the beet roots deviate too far, and the harvesting effect cannot meet the design requirements, which needs further improvement and optimization.

## 5 Conclusions

1) Using a self-developed sugar beet combine harvester and field simulation test bench, based on the preliminary single factor bench test of the automatic row following system, three-factor three level orthogonal tests, including the first-order interaction of various factors, research on parameter optimization of the automatic row following system were performed. The forward speed, hydraulic flow, and spring preload which have significant impacts on the performance indicators are taken as the test factors, and the missed excavation rate, breakage rate, and response time are taken as the performance indicators.

2) The range and variance analysis of the orthogonal test results show that there are differences in the influence degree, primary and secondary order, and the optimal parameter combination of various factors and their first-order interactions on each performance indicator. For the response time indicator, the optimal parameter combination is $A_2B_1C_3$; for the missed excavation rate indicator, the optimal parameter combination is $A_3B_3C_1$; and the breakage rate is $A_2B_2C_1$. Using the weighted comprehensive scoring method, the optimal parameter combination of the overall operation performance of the automatic row following system is $A_2B_2C_1$, that is, the hydraulic flow is 25 L/min, the operation forward speed is 0.8 m/s, and the spring preload is 198 *N*. Under this combination, the response time of the automatic row following excavation and harvesting system is 0.496 s, the missed excavation rate is 2.35%, and the breakage rate is 3.65%.

3) To verify the optimization results of the bench test parameters and investigate the smoothness and adaptability of the automatic row following system, field verification tests with different ridge shapes and different planting patterns were carried out. The results showed that the average missed excavation rates of conventional straight ridges and extremely large “S”-shaped ridges were 2.23% and 2.69%, and the maxima were 2.39% and 2.98%, respectively. The average breakage rates were 3.38% and 4.14%, respectively, and the maximum values were 3.58% and 4.48%, respectively, which were all within the design requirements

of the performance indicators. The automatic row following system has good overall adaptability to different planting agronomies and meets the harvesting requirements and industrial standard for the operation quality of sugar beet harvesters. This study can provide a reference for research on automatic row following harvesting systems of sugar beets and other subsoil crop harvesters, such as white radish harvesters, peanut harvesters, potato harvesters, etc.

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