Formation mechanism for the laying angle of hemp harvester based on ANSYS-ADAMS

Jicheng Huang[1,2,3], Li Tan[3], Kunpeng Tian[1,2,3], Bin Zhang[2], Aimin Ji[3*], Haolu Liu[2], Cheng Shen[1,2*]

(1. *Key Laboratory of Modern Agricultural Equipment and Technology, Jiangsu University, Ministry of Education, Zhenjiang 212013, Jiangsu, China*;
2. *Nanjing Institute of Agricultural Mechanization, Ministry of Agriculture and Rural Affairs, Nanjing 210014, China*;
3. *College of Mechanical and Electrical Engineering, Hohai University, Changzhou 213022, Jiangsu, China*)

Abstract: Aiming at the problem of large differences in the laying angle and posture of plants cut by the hemp harvester, which is unfavorable for the subsequent picking-up, this paper analyzed the laying process and laying angles, and built a conveyor-plant rigid-flexible coupling model for simulating the laying of hemp plant. Moreover, the operating parameters were tested and optimized based on the central composite design theory, and carried out multi-objective optimization with the minimum laying angle as the response index. Firstly, the formation mechanism of the laying angle of hemp harvester was studied. Secondly, a test was designed with the quadratic orthogonal rotational combination test method, with the data being processed by Design-Expert. A regression mathematical model of the laying angle was built, and the influence of the interactions between factors on the laying angle was analyzed with the response surface method. Furthermore, multi-objective optimization was conducted on the regression model according to the actual production design requirements. As a result, the best combination was obtained, that is, when the forward speed is 0.7 m/s, speed ratio 1.40, and stubble height 95 mm, the minimum laying angle can be obtained, namely 124.9°. The optimization parameters were verified by the simulation and field tests. The simulation test showed that the simulated laying angle is 125.2°, with a relative error of 0.24% from the theoretical value, under the best combination of parameters. The field test showed that the average laying angle of hemp plant is 121.8°, with a relative error of 2.5% from the theoretical value, under the best combination of parameters. The results may provide a reference for the structural improvement and operating parameter control of hemp harvesters.

Keywords: agricultural machinery, hemp, laying angle, rigid-flexible coupling model, optimization, response surface analysis
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1 Introduction

Hemp application mainly covers four areas: fiber use, combined medicinal-fiber use, medicinal use of its flowers and leaves, and seed use. Different applications vary greatly in the methods of harvesting[1,2]. Hemp cultivated in Europe and America is grown mainly for short fiber application and medicinal ingredient extraction, and hemp harvesters include stem-leaf harvesters, stalk harvesters, stem-leaf-seed harvesters, etc.[3-5]. In China, hemp is grown mainly for long fiber textile, and the whole stalk is cut by hemp harvester and then evenly and neatly laid out in the field for drying[6-9]. Due to the biological features of hemp, such as thick and tall stalks, easy to break and twist, there may be great differences in the laying angle and postures during harvesting, which is not conductive to subsequent picking-up. Laying angle is one of the important performance indexes for evaluating hemp harvesters, and the study on the formation mechanism of laying angle may provide a basis for the design and optimization of hemp harvesters.

With regard to the formation mechanism of laying angle, domestic and foreign scholars mostly study the main factors affecting the laying quality by combining the dynamics and kinematics. Li et al.[10] analyzed the motion parameters, structural parameters, and influence law of geometric parameters on the laying angle of the arc-track-type flexible holding conveyor of whole-stalk sugar cane harvester, and showed that when the conveying speed increases, the laying angle increases; when the forward speed increases, the laying angle decreases; and the clamping height has little influence on the laying angle. Li et al.[11] analyzed the influence law of the ratio between the conveyor chain speed and forward speed, the forward speed and stubble height on the laying angle of rape cutter-rower using ANSYS and ADAMS software. The field test showed that with optimized operating parameters, the relative error between the predicted value and measured value of the laying angle is less than 6%, and the laying angle decreases from 134.9° to 115.8°, demonstrating better perfomance. Shu et al.[12] conducted the multi-body dynamics simulation of the forward side-laying of rape stalks, and built an optimization objective function with the forward speed, speed ratio of horizontal conveyor chain and header inclination as factors and

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Biographies: Jicheng Huang, Associate Professor, research interest: agricultural mechanization engineering, Email: huangjicheng@caas.cn; **Li Tan**, MS, research interest: agricultural mechanization engineering, Email: tanli26@163.com; **Kunpeng Tian**, Assistant Professor, research interest: agricultural mechanization engineering, Email: tiankp2005@163.com; **Bin Zhang**, Professor, research interest: agricultural engineering, Email: xtsset@hotmail.com; **Haolu Liu**, Research Assistant, research interest: agricultural engineering, Email: liuhaolu@caas.cn.
***Corresponding author: Aimin Ji**, PhD, Professor, research interest: mechanical mechanism optimization. College of Mechanical and Electrical Engineering, Hohai University, No.200 North Jinling, Xinbei District, Changzhou 213022, China. Email: jiam@hhuc.edu.cn; **Cheng Shen**, Assistant Professor, research interest: agricultural mechanization engineering. Nanjing Institute of Agricultural Mechanization, No.100 Liuying, Xuanwu District, Nanjing 210014, China. Tel: +86-25-84346078, Email: shencheng@caas.cn.

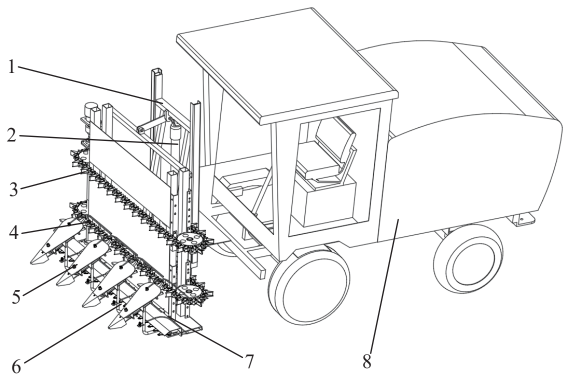
minimum laying angle as the objective. The theoretical best laying angle was 15.25°, the simulated laying angle was 14.42°, and the average laying angle of rape stalk in field test was 17.25°. The test results can provide references for the structural improvement and optimization of the laying device of vertical rape cutter-roller.

Aiming at the special biological characteristics of hemp stalks, this paper developed a multi-body dynamics model for conveyor-plant rigid-flexible coupling of hemp harvester, using ANSYS and ADAMS software, visualized the posture change of stalks in the process of clamping and conveying, grain discharge opening, landing and laying of stalks, studied the influence law of operating parameters on the laying angle, and conducted the simulation and field test for verification, in order to guide the field operation of hemp harvester and provide references for the improvement design of hemp harvester.

2 Overall structure and operating principle

2.1 Overall structure

The hemp harvester consists of a wheeled chassis, a header frame, a double-knife reciprocating cutter, upper and lower chain conveyors, a grain splitting and supporting device, etc. The overall structure is shown in Figure 1.



1.Header frame; 2.Header lifting cylinder; 3.Upper chain conveyor; 4.Lower chain conveyor; 5.Grain splitting and supporting device; 6.Double-knife reciprocating cutter 7.Pressure spring 8.Wheeled chassis

Figure 1 General structure schematic of hemp harvester

The header is mounted in front of the wheeled chassis and the stubble height can be controlled by the lifting cylinder of the header; the double-knife reciprocating cutter is mounted at the bottom of the header; the upper and lower chain conveyors are mounted parallel to the upper and lower parts of the header frame; and the grain splitting and supporting device extends in front of the frame. Its main technical parameters are listed in Table 1.

Table 1 Main technical parameters of hemp harvester

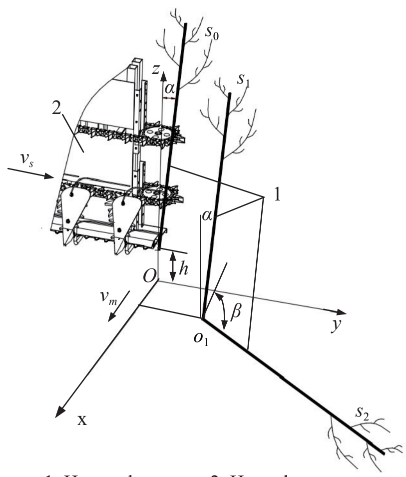
Parameters	Value
Chassis power/kW	74.5
Cutting width/mm	1600
Operating speed/m·s^{-1}	0.5-1.0
Horizontal conveyor chain speed/m·s^{-1}	0.6-1.4
Stubble height/mm	60-140
Operating efficiency/hm^2·h^{-1}	0.4-0.6

2.2 Operating principle

During operation, hemp harvester adjusts the header height through the lifting cylinder, so as to meet the design requirements on stubble height. With grain splitting and supporting device, stalks within the operating width are plucked up and guided into the double-knife reciprocating cutter for cutting. Later, the cut stalks are clamped and conveyed to the right of the header under the combined action of the upper and lower chain conveyors and pressure spring. Hemp plants, after leaving the horizontal conveyor chain, are laid to the right of the header under the inertial force of weight, horizontal conveyor chain and forward speed of the harvester, and the whole operation process completes.

3 Analysis of laying process and laying angle

According to the literatures[13,14], the laying process of hemp plant includes two consecutive processes, namely the falling from position S_0 to position S_1, and the rotation process from position S_1 to the landing position S_2, as shown in Figure 2. The stubble height is h, the plant inclination angle is α, the machine forward speed is v_m, the horizontal chain conveyor speed is v_s, the initial position of hemp plant is S_0, the contact position with the ground is S_1, and the final landing position is S_2.



1. Hemp plant 2. Hemp harvester

Figure 2 Schematic diagram of the hemp plant laying process

A right-angle coordinate system xyz was established on the ground, with the projection point of the lower end of hemp plant at the moment when it left the header on the ground as the origin O, the forward direction of the harvester as x axis, horizontal chain conveying direction as y axis, and vertical-up direction as z axis. Hemp plants fell with horizontal projectile movement tracks in the three-dimensional space, with the displacement and velocity being expressed in Equations (1) and (2) respectively when touching the ground.

$$\begin{cases} x_t = v_m \cdot \sqrt{2h/g} \\ y_t = v_s \cdot \sqrt{2h/g} \\ z_t = 0 \end{cases} \tag{1}$$

$$\begin{cases} v_x = v_m \\ v_y = v_s \\ v_z = -\sqrt{2h/g} \end{cases} \tag{2}$$

The resultant velocity of plants was:

$$v = \sqrt{v_x + v_y + v_z} = \sqrt{v_m^2 + v_s^2 + 2gh} \tag{3}$$

where, x_t is the coordinate of the bottom of the hemp plants on the x axis; y_t is the coordinate of the bottom of the hemp plants on the y axis; z_t is the coordinate of the bottom of the hemp plants on the z axis; h is the distance between the bottom of the hemp plant and the ground, m; g is the acceleration of gravity, 9.8 m/s^2; v_m is the forward speed of hemp harvester, m/s; v_s is the lateral conveyor chain speed, m/s; v_x is the velocity of the bottom of the hemp plants in the x direction, m/s; v_y is the velocity of he bottom of the hemp plants in the y direction, m/s.

Based on the practical situation in the field of hemp plants, it was supposed that complete inelastic collision occurred when the bottom of hemp plants touched the ground. After landing, hemp plants rotated around the landing point O_1 from the flat motion in the space, as shown in Figure 3. The angle between v and hemp plant before the collision is δ, $\delta=\theta+\alpha$, where $\theta=\arctan\sqrt{(v_s^2+v_m^2)/2gh}$. Let the fixed-axis rotating angular velocity after collision be ω_1, so the equation of motion of hemp plants from flat motion to rotation is:

$$J\cdot\omega_1=m\cdot l_0\cdot v\cdot\sin\delta \tag{4}$$

where, J is the moment of inertia of hemp plants around O_1, kg·m^2; l_0 is the distance from the center of mass to the bottom of hemp plants, m; m is the mass of plant, kg; ω_1 is the angular velocity after collision, rad/s; v is the resultant velocity of plants, m/s.

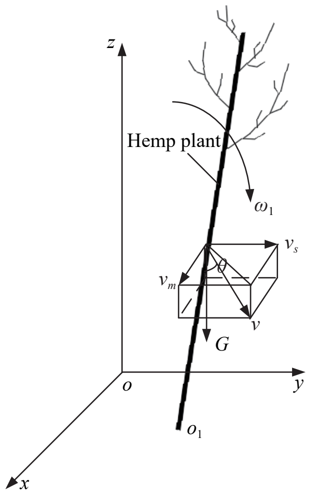


Figure 3 Analysis of landing process of hemp plants

Based on the above equation,

$$\omega_1=\frac{m\cdot l_0\cdot\sin\delta\sqrt{v_s^2+v_m^2+2gh}}{J} \tag{5}$$

Based on the kinetic energy theorem of fixed-axis rotation of hemp plants around O_1,

$$Gl_0\cos\alpha=\frac{1}{2}J\left(\omega_2^2-\omega_1^2\right) \tag{6}$$

where, G is the gravity of hemp plants, N; ω_1 is the angular velocity after collision, rad/s; ω_2 is the instantaneous angular velocity of laying on the ground, rad/s.

From equation (6), the instantaneous angular velocity of plant laid on the ground is

$$\omega_2=\frac{\sqrt{2JGl_0\cos\alpha+m^2l_0^2\sin^2\delta(v_s^2+v_m^2+2gh)}}{J} \tag{7}$$

$$\omega_2-\omega_1=\frac{\sqrt{2JGl_0\cos\alpha+m^2l_0^2\sin^2\delta(v_s^2+v_m^2+2gh)}}{J}-\frac{ml_0\sin\delta\sqrt{(v_s^2+v_m^2+2gh)}}{J} \tag{8}$$

According to the angular momentum theorem,

$$Gl_0\sin\varphi=J\frac{\mathrm{d}\omega}{\mathrm{d}t} \tag{9}$$

where, φ is the angle between the stalk and z axis in the laying process, (°).

From Equation (9), the time of movement of hemp plants during rotation is

$$t=\frac{J(\omega_2-\omega_1)}{Gl_0(1-\sin\alpha)} \tag{10}$$

The laying angle is defined as the rear included angle between hemp stalks and the forward direction of the harvester after laying, so the theoretical laying angle β is expressed as:

$$\beta=\frac{\pi}{2}+\alpha_1+\arcsin\frac{v_mt}{l} \tag{11}$$

By substituting Equations (8) and (10) into Equation (11), the theoretical laying angle can be calculated as

$$\beta=\frac{\pi}{2}+\alpha_1+\arcsin M \tag{12}$$

$$M=\frac{v_mt}{l}=\frac{v_m}{Gll_0(1-\sin\alpha)}\cdot\left[\sqrt{2JGl_0\cos\alpha+m^2l_0^2\sin^2\delta(v_s^2+v_m^2+2gh)}-ml_0\sin\delta\sqrt{v_s^2+v_m^2+2gh}\right] \tag{13}$$

where, l is the total length of the hemp plant, m; α_1 is the projection of the plant inclination α on the plane xoy.

Based on Equation (13), the laying angle is related to the forward speed v_m, the lateral chain conveyor speed v_s, the total plant length l, the stubble height h, and the total mass of plants m.

4 Rigid-flexible coupling multi-body dynamics model building

4.1 Building flexible mechanical model of hemp plants

According to the phenotypic parameters and mechanical-physical properties of hemp plants in the literature[15-18], a three-dimensional model of hemp stalks was built, with hemp stalks as orthotropic material, and the properties[19] of whole hemp stalks were added in ANSYS, as shown in Figure 4.

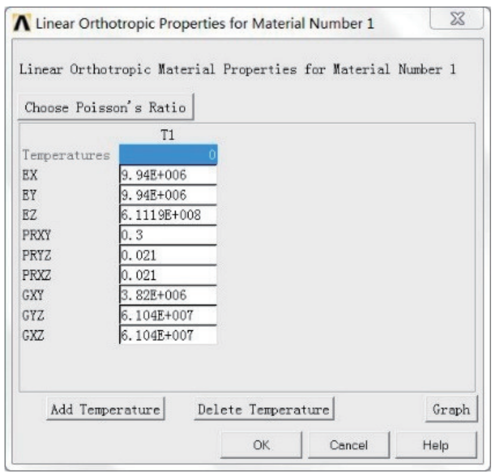


Figure 4 Hemp stalk material properties

SOLID186 cell was selected as the material cell and Orthotropic as the material type. Considering the calculation accuracy and subsequent dynamics simulation calculation amount, smart size was defined as the meshing of stalk model, and a finite element mesh model with 19 000 nodes and 90 000 cells was generated. In addition a rigid domain connection point was created respectively on the top and at the bottom of the stalk. A flexible body model containing stalk shape, mechanical characteristics and other parameters of hemp plants was exported using the Export to

ADAMS function of ANSYS, and saved as a .mnf file.

4.2 Rigid-flexible coupling model building

A 3D model of hemp harvester conveyor was built in ProE. To reduce the ADAMS simulation calculation time, hydraulic motor, chain guide, frame and other parts were removed, and the conveyor chain was simplified, but the upper and lower pressure spring, upper and lower horizontal conveyor chain were reserved. The simplified conveyor model was saved as a .x_t file and imported into ADAMS. The generated plant flexible mechanical model in .mnf format was opened in the specified directory through the Flexible Bodies option of ADAMS to build the conveyor-plant rigid-flexible coupling model of the hemp harvester. The model is shown in Figure 5 in ADAMS.

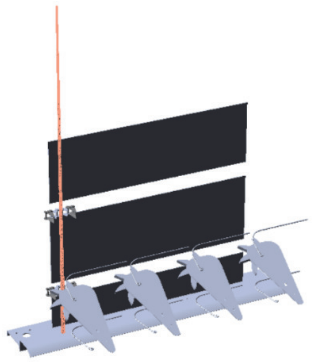


Figure 5 Rigid-flexible coupling dynamic simulation model

4.3 Adding constraints, drives and contacts

Based on the theoretical analysis of the laying process of hemp harvester and actual situation, constraints, drives and contacts were defined in the dynamic simulation model.

1) The kinematic pair between the pressure spring and ground was defined as linear pair, and the motion direction as the forward direction, and a constant translational drive was added. The kinematic pair between the horizontal conveyor chain and the ground was defined as the planar pair, and the motion direction was obtained by directly adding the forward direction drive and the conveyor direction drive.

2) Contact force between hemp plants and the compression spring was added, whose contact type was flex body to solid and contact force was impact[20,21]. The stiffness coefficient, collision index, maximum damping coefficient and cut depth were defined as 22.27 N/mm, 2, 0.22 N·s/mm and 0.1 mm respectively, and the static friction coefficient, dynamic friction coefficient, static translational and dynamic translational velocity were defined as 0.30, 0.25, 0.1 mm/s and 10 mm/s, respectively. Contact force between hemp plants and conveyor chain was added, whose contact type was flex body to solid and contact force was impact. The stiffness coefficient, collision index, maximum damping coefficient and cut depth were defined as 47.38 N/mm, 2, 0.47 N·s/mm and 0.1 mm, respectively, and the static friction coefficient, dynamic friction coefficient, static translational and dynamic translational velocity were defined as 0.30, 0.25, 0.1 mm/s and 10 mm/s respectively. Contact force between hemp plants and the ground was added, whose contact type was Flex Body to Solid and Contact Force was Impact. The stiffness coefficient, collision index, maximum damping coefficient and cut depth were defined as 100 kN/mm, 2, 10 N·s/mm and 0.1 mm, respectively, and the static friction coefficient, dynamic friction coefficient, static translational and dynamic translational velocity were defined as 0.6, 0.5, 0.1 mm/s and 10 mm/s, respectively.

4.4 Adding sensors

During the process of laying simulation by ADAMS, the motion process of hemp plants was divided by adding two sensors. One was the displacement sensor between the bottom of hemp plants and the ground; when the bottom of hemp plants moved a certain distance in the vertical direction (the distance was from the bottom to the ground), the sensor failed, and the falling of hemp plants completed. The other was the displacement sensor at the top of hemp plants and the ground, when the top of hemp plants moved a certain distance in the vertical direction (the distance was from the top to the ground), the sensor failed, and the laying of hemp plants completed.

5 Test results and analysis

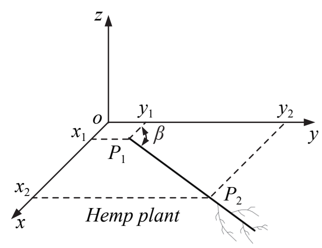
5.1 Test factors and evaluation indexes

The response surface test[22,23] was conducted with the machine forward speed A, the speed ratio between the horizontal conveyor chain speed and forward speed *B*, and stubble height *C* as test factors and laying angle *Y* between the plant stalk and negative direction of forward speed as the evaluation index, and the coding table of factors and levels is listed in Table 2.

Table 2 Coding table of test factors and levels

Factor	Test level		
	–1	0	1
Forward speed A/m·s^{-1}	0.5	0.75	1.0
Speed ratio B	1.2	1.3	1.4
Stubble height C/mm	60	100	140

To achieve the laying angle of hemp plants after harvesting, the direction of forward speed was defined as the positive direction of the x axis, the direction of horizontal conveyor chain speed as the positive direction of the y axis, and the gravity direction as the opposite direction of the z axis. Two marker points P_1 and P_2 were set on the stalk of hemp plant, as shown in Figure 6.



Note: P_1 is the bottom connection point on hemp plant, and P_2 is the top connection point on hemp plant.

Figure 6 Schematic diagram of laying angle

According to the motion process analysis of hemp plants, the simulated laying angle β could be calculated as:

$$\beta = \frac{\pi}{2} + \arctan\frac{x_2 - x_1}{y_2 - y_1} \tag{14}$$

where, x_1 is the coordinate of P_1 on the x axis; x_2 for P_2 on the x axis; y_1 for P_1 on the y axis, and y_2 for P_2 on the y axis.

To facilitate understanding the change of laying angle in the laying process, a measurement function of the angle between the hemp plant and the global coordinate system x in the negative direction was established in the Function Builder module of ADAMS. The total simulation time and simulation steps were set by script simulation. After the simulation, the data of laying angle varying with time were exported from the Post processor module of ADAMS, and the change curve of laying angle with time in the laying process was obtained after data fitting, as shown in Figure 7 (the laying angle simulation curve of 6 in Table 3).

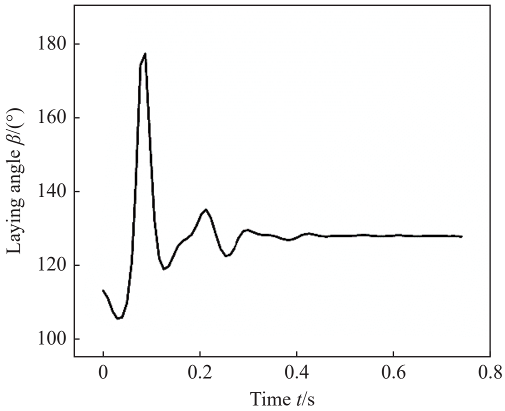


Figure 7 Variation curve of laying angle with time

Table 3 Results and design of tests

No.	Forward speed A/m·s⁻¹	Speed ratio B	Stubble height C/mm	Laying angle Y/(°)
1	–1	0	–1	127.6
2	1	1	0	125.5
3	0	–1	–1	131.4
4	0	–1	1	130.1
5	0	1	1	126.3
6	0	0	0	127.5
7	1	0	–1	130.1
8	–1	–1	0	129.0
9	1	–1	0	129.6
10	0	0	0	127.5
11	0	0	0	127.5
12	0	0	0	127.5
13	1	0	1	128.3
14	–1	1	0	124.5
15	–1	0	1	127.2
16	0	1	–1	125.5
17	0	0	0	127.5

5.2 Multi-factor response surface test results and analysis

The multi-factor test design and results are listed in Table 3.

The quadratic regression analysis was conducted for the test results with Design-Expert software, and multiple regression fitting was carried out to obtain the regression equation of the laying angle *Y* in terms of the forward speed *A*, speed ratio *B* and stubble height *C*, and the equations was as follows:

$$Y = 127.50 + 0.65A - 2.29B - 0.34C + 0.10AB - 0.35AC + 0.53BC - 0.19A^2 - 0.16B^2 + 0.99C^2 \quad (15)$$

Further analysis was conducted for the above equation, and in the meantime, significance tests were conducted for the regression coefficients[24,25], as listed in Table 4.

Table 4 Analysis of variance of laying angle

VarianceSource	Sum of squares	*DoF*	*F*-value	*p*
Model	52.03	9	39.97	<0.000 1**
A	3.38	1	23.37	0.0019**
B	41.86	1	289.41	<0.000 1**
C	0.91	1	6.30	0.040 4*
AB	0.040	1	0.28	0.615 2
AC	0.49	1	3.39	0.108 3
BC	1.10	1	7.62	0.028 1*
A^2	0.15	1	1.02	0.345 4
B^2	0.11	1	0.77	0.409 7
C^2	4.11	1	28.39	0.001 1**
Residual	1.01	7		
Lack of fit	1.01	3	0.34	
Error	0.00	4		
Total	53.04	16		

Note: **Extremely significant (p<0.01); *Significant (p<0.05).

According to the analysis results in Table 4, the response surface model *P* of the laying angle *Y* is <0.0001, less than 0.01, meaning that the significance of the final model meets the requirements. The coefficient of determination R^2 of the model is 0.9809, indicating a good fit, and high reliability of the response surface analysis results. Therefore, the model can be used for predicting and analyzing the changes of operating performance of hemp harvesters.

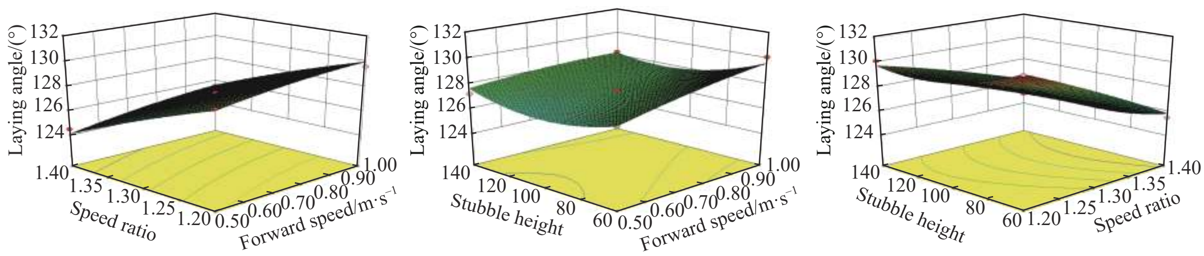
According to the above significance analysis, *A, B,* and C^2 in the response surface model of the laying angle *Y* have a significant influence on this model, while *C* and *BC* also had a significant influence on this model. Items with an insignificant influence on the regression model in the above model were eliminated, and the simplified regression model was obtained on the premise of ensuring model p<0.01 and misfit term p>0.05 as follows:

$$Y = 127.50 + 0.65A - 2.29B - 0.34C + 0.53BC + 0.99C^2 \quad (16)$$

The test results indicated that the influence of factors on the laying angle were rated in descending order: speed ratio between horizontal conveyor chain speed and forward speed, harvester forward speed, stubble height.

To explore the interactions of factors in the regression equation, a response surface curve was established for the influence of speed ratio between horizontal conveyor chain speed and forward speed, harvester forward speed, and stubble height on the laying angle, as shown in Figure 8.

Figure 8a shows the response surface diagram of the interaction between the forward speed and speed ratio on the laying angle, when the stubble height is at an intermediate level, which indicates



a. *C*=100 mm b. *B*=1.3 c. *A*=0.75 m/s

Figure 8 Influence of interaction on laying angle that the interaction between the two factors is not significant. When the speed ratio is constant, the laying angle increases first and then decreases with the increase of the forward speed. When the forward speed is constant, the laying angle decreases with the increase of the speed ratio. In the interaction between the forward speed and speed ratio on the laying angle, the forward speed has a greater influence on the interaction.

Figure 8b shows the response surface diagram of the interaction between the forward speed and stubble height on the laying angle, when the speed ratio is at an intermediate level, i.e. B=1.3, which indicates that the interaction between the two factors is not significant. When the forward speed is constant, the laying angle decreases first and then increases with the increase of the stubble height. When the stubble height is constant, the laying angle increases with the increase of the forward speed. In the interaction between the forward speed and stubble height on the laying angle, the forward speed has a greater influence on the interaction.

Figure 8c shows the response surface diagram of the interaction between the speed ratio and stubble height on the laying angle, when the forward speed is at an intermediate level, i.e. A=0.75 m/s, which indicates that the interaction between the two factors is significant. When the speed ratio is constant, the laying angle decreases first and then increases with the increase of the stubble height. When the stubble height is constant, the laying angle decreases with the increase of the speed ratio. In the interaction between the speed ratio and stubble height on the laying angle, the speed ratio has a greater influence on the interaction.

5.3 Parameter optimization and test verification

The forward speed, speed ratio between horizontal conveyor chain speed and forward speed, and stubble height had different influences on the laying angle. To clarify the best combination of parameters of hemp harvester, parameters of multiple targets shall be optimized. According to the actual production requirements and other relevant standards, the operating efficiency shall be more than 0.45 hm^2/h, the forward speed shall be over 0.7 m/s, and stubble height shall be less than 100 mm, and an optimization model was established.

$$\begin{cases} \min Y = \{A, B, C\} \\ St: \begin{cases} 0.7 \text{ m/s} \leq A \leq 1.0 \text{ m/s} \\ 1.2 \leq B \leq 1.4 \\ 60 \text{ mm} \leq C \leq 100 \text{ mm} \end{cases} \end{cases} \tag{17}$$

Parameters were optimized with Design-Expert to get the optimal solution: forward speed 0.7 m/s, speed ratio 1.4, and stubble height 95 mm, and at this moment, the laying angle was 124.9°.

To verify the accuracy of the best solution, test verification was conducted for the best combination of parameters in ADAMS. The simulated laying angle was 125.2°, with a relative error of 0.24% from the theoretical optimal laying angle, which is basically consistent with the theoretical value.

To further verify the accuracy of the model, the validation test was carried out from August 3 to 5, 2022, in Subei Village, Hanbaidu Town, Yu'an District, Lu'an City, Anhui Province, as shown in Figure 9. The hemp for test was Anhui Hemp No. 1, which was planted by direct seeding. The planting density was 23.3 plants/m^2, the average plant height was 4.5 m, the test parameters were under forward speed of 0.7 m/s, speed ratio of 1.4, stubble height of 95 mm, the field laying angle measurement is shown in Figure 10.

Figure 9 Field testing of hemp harvester

Figure 10 Field laying angle measurement

After the operation of hemp harvester was completed, refer to the standards JB/T7733-2007 *Swather. Techniacl Requirements* and GB/T8097-2008 *Equipment for Harvesting*, *Combine Harvesters*, *Test Procedure*, to measure the indicators of swather operations. The specific measurement method is as follows: The tape measure was fixed parallel to the laying strip, and a test area of 1 m was selected every 2 m. The angle ruler was used to measure the angle between the main stalk of hemp and the tape measure in the test area, and the data were recorded and averaged. Then the hemp laying angle was β.

$$\beta = \frac{1}{10}\sum_{i=1}^{10}\beta_i,\ i = 1, 2, \ldots, 10 \tag{18}$$

where, β_i is the average value of the laying angle within each measurement area, (°).

The average laying angle was measured to be 121.8°, and the relative error was 2.5%. The main reasons for this relative error were simulation steps, air resistance, traction force between hemp stalks, and friction between hemp stalks and baffles, etc.

6 Conclusions

(1) This paper explained the structure and operating principle of hemp harvester, analyzed the horizontal projectile motion of stalks at the grain discharge opening and fixed-axis rotation process after landing, and clarified the main factors affecting the laying angle, namely the forward speed, speed ratio of horizontal conveyor chain speed and forward speed, and stubble height.

(2) Hemp harvester conveyor model and plant flexible body model were built respectively with ProE software and ANSYS software, which were introduced into ADAMS to build the conveyor - plant rigid-flexible coupling model.

(3) The Box-Behnken simulation test was carried out based on ADAMS, with the minimum laying angle as the target of optimization, the best combination of parameters was obtained, namely forward speed 0.7 m/s, the speed ratio 1.4, and the stubble

height 95 mm, at which the laying angle was 124.9°. The laying angle obtained in the field test was 121.8°, with a relative error of 2.5% from the theoretical optimal value.

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[References]

[1] Xiong H P. National bast fiber industry technology development report. Beijing: China Agricultural Science and Technology Press, 2019.

[2] Xiang W, Li B H, Ma L, Liu J J, Yan B, Duan Y P, Lv J N. Review of mechanization harvesting technique for industrial hemp. Plant Fiber Sciences in China, 2022; 44(3): 190–200. (in Chinese)

[3] Shen C, Liang S M, Liang J H, Liu H L, Huang J C, Tian K P, et al. Status of hemp field production mechanization and research thoughts for China's hemp production areas. International Agricultural Engineering Journal, 2020; 29(3): 194–204.

[4] Pari L, Baraniecki P, Kaniewski R, Scarfone A. Harvesting strategies of bast fiber crops in Europe and in China. Industrial Crops and Products, 2015; 68: 90–96.

[5] Henryk B, Ryszard K. New technology of harvesting hemp grown for seed. Journal of Industrial Hemp, 2005; 10(1): 49–60.

[6] Huang J C, Shen C, Ji A M, Tian K P, Zhang B, Li X W, et al. Design and test of two-wheeled walking hemp harvester. Int J Agric & Biol Eng, 2020; 13(1): 127–137.

[7] Zhu H, Zhang Z G, Yu G. Development and test of hemp swather. Agricultural Engineering, 2018; 8(2): 95–98. (in Chinese)

[8] Huang J C, Shen C, Ji A M, Li X W, Zhang B, Tian K P, et al. Optimization of cutting-conveying key working parameters of hemp harvester. Journal of Jilin University (Engineering and Technology Edition), 2021; 51(2): 772–780. (in Chinese)

[9] Huang J C, Shen C, Li X W, Tian K P, Chen Q M, Zhang B. Design and tests of hemp harvester. International Agricultural Engineering Journal, 2017; 26(2): 117–127.

[10] Li Z H, Qu Y G. Windrowing kinematics analysis of sugarcane on whole stalk sugarcane harvester. Transaction of the CSAE, 2008; 24(11): 103–108. (in Chinese)

[11] Li H T, Wu C Y, Mu S L, Guan Z H, Jiang T. Formation mechanism of laying angle of vertical rape windrower based on ANSYS-ADAMS. Transactions of the CSAE, 2020; 36(14): 96–105. (in Chinese)

[12] Shu C X, Cao S C, Liao Y T, Liao Q X, Wan X Y, Li Y T. Laying device for rape windrower based on ADAMS. Transactions of the CSAM, 2022; 53(S2): 11–19, 38. (in Chinese)

[13] Wang X S, Liu D W, Li X, Xie F P, Wu M L, Luo H F. Design and experiment of 4SY-2.0 self-propelled rape windrower. Journal of Hunan Agricultural University (Natural Sciences), 2016; 42(4): 445–453. (in Chinese)

[14] Shi Z X, Xie W, Ren S G, Wu M L, Yang W M, Xiang W. Design and test of 4SY-2.2 rape windrower. Chinese Agricultural Science Bulletin, 2017; 33(10): 140–145. (in Chinese)

[15] Zhou Y, Li X W, Shen C, Tian K P, Zhang B, Huang J C. Experimental analysis on mechanical model of industrial hemp stalk. Transaction of CSAE, 2016; 32(9): 22–29. (in Chinese)

[16] Shen C, Zhang B, Li X W, Yin G D, Chen Q M, Xia C H. Bench cutting tests and analysis for harvesting hemp stalk. Int J Agric & Biol Eng, 2017; 10(6): 56–67.

[17] Shen C, Chen Q M, Li X W, Tian K P, Huang J C, Zhang B. Experimental analysis on single-stalk cutting of hemp. International Agricultural Engineering Journal, 2016; 25(4): 87–196.

[18] Ma L, Liu J J, Zhou W, Xiang W, Lv J N, Wen Q H. Test of axial mechanical compressive properties for industrial hemp dry stalk. Journal of Chinese Agricultural Mechanization, 2018; 39(11): 34–40, 50. (in Chinese)

[19] Zhou Y, Li X W, Shen C, Tian K P, Zhang B, Huang J C. Research of industrial hemp mechanization harvester technology. Journal of Agricultural Mechanization Research, 2017; 5: 42–45, 51. (in Chinese)

[20] Pei W C, Li Y G, Li Y H. V The impact force models based on the virtual prototype-ADAMS. Journal of Hebei Polytechnic University (Natural Science Edition), 2008; 30(4): 59–63. (in Chinese)

[21] An X B, Pan S F. Analysis of contact model in multi-body system dynamic simulation. Computer Simulation, 2008; 25(10): 98–101. (in Chinese)

[22] Xu X H, He M Z. Experimental design and application of Design-Expert SPSS. Beijing: Science Press Co., Ltd, 2006. (in Chinese)

[23] Pan L J, Chen J Q. Experimental design and data processing. Nanjing: Southeast University Press, 2008. (in Chinese)

[24] Shen G W, Wang G P, Hu L L, Yuan J N, Wang Y M, Wu T, et al. Development of harvesting mechanism for stem tips of sweet potatoes. Transactions of the CSAE, 2019; 35(19): 46–55. (in Chinese)

[25] Yang G, Chen Q M, Xia X F, Chen J N, Song Z Y. Design and optimization of the key components for 4DL-5A faba bean combine harvester. Transactions of the CSAE, 2021; 37(23): 10–18. (in Chinese)