Design and Prototype Test of key components of Segmented Ligusticum wallichii Harvester

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Abstract. According to the harvest demand of Ligusticum wallichii, a segmented Ligusticum wallichii harvester was designed. The crushing device was set in the front end of tractor and the vibrating harvester was mounted in the rear end of tractor. Firstly, the strength test of Ligusticum wallichii stalks was carried out, and the basic parameters of the crushing device were determined. The results showed that the minimum required speed of the crushing device was 3880r/min. Secondly, the vibration structure was modeled and analyzed by vector equation, and the vibration structure was simulated and analyzed by ADAMS, and the parameters of the vibration structure were determined. The results showed that when the crank angle was 22~100\textdegree, the Ligusticum wallichii-soil mixture was thrown backward away from the vibration steel bar, and throw away distance was 88.42mm. Finally, the field prototype test was carried out. During the test, the crushing device could crush the stems of Ligusticum wallichii normally. The rotational speed was measured at 4020r/min. The obvious rate, loss rate and damage rate of Ligusticum wallichii stem were calculated. The stems obvious rate was 95\%, loss rate was 4.5\% and damage rate was 0.4\%, which met the harvest requirements of Ligusticum wallichii.

1. Introduction

Ligusticum wallichii is an Umbelliferae plant, which has the functions of promoting blood circulation, anti-inflammation and relieving depression\textsuperscript{[1]}. The stems of Ligusticum wallichii is 40-60 cm high, and the rhizome is an irregular nodular fist-shaped mass, and its mature lower stems node is expanded into a disk-like shape (Grifola frondosa). Sichuan is the province with the largest Ligusticum wallichii planting area in China, mainly in Meishan, Pengzhou, and Dujiangyan\textsuperscript{[2]}. In recent years, the planting area of Ligusticum wallichii in Chengdu Plain is over 90,000 Mu, accounting for more than 90\% of the planting area of Ligusticum wallichii in China.

A great deal of research has been done on harvesting machinery at home and abroad, for example, the United States, Germany, Japan and other countries, such as the development of harvesting machinery for radish, potato and peanut\textsuperscript{[3]}, and the research on harvesting machines for medicinal materials with long roots in China. For example, Zhang Zhaoguo and others conducted motion analysis and test on the digging and soil removing device of Panax notoginseng harvester\textsuperscript{[4]}, and studied the design and test of Glycyrrhiza uralensis harvester\textsuperscript{[5]}. The current harvester is not suitable for the Chuanxiong harvesting mode, that is, the stalks on the surface need to be crushed before harvesting, however, the current harvester used for the harvesting of Ligusticum wallichii will cause soil clogging, which causes the harvester to fail to work normally.
In this paper, a segmented Ligusticum wallichii harvester is designed, the rotational speed of crushing device is designed and calculated, the kinematics theory analysis and simulation verification of the vibration of harvesting device are carried out, the motion law of vibration mechanism is obtained, the field test of the prototype is carried out, and the harvesting performance of the prototype is verified by the standard of the medicinal material harvester.

2. Overall design of Ligusticum wallichii harvester

The structure of the designed segmented Ligusticum wallichii harvester is shown in Figure 1. The whole machine includes crushing device, tractor and vibrating harvester. The vibrating harvester includes digging shovel, vibrating mechanism and conveying mechanism. According to the width of Ligusticum wallichii, the working width of the whole machine is designed to be 1550mm, and the digging angle is 10–20°. The working principle of the whole machine is that the tractor runs forward. The crushing device rotates the hydraulic motor through the hydraulic oil provided by the tractor, so that the straw rope of the crushing device rotates at high speed, crushing the stems of Ligusticum wallichii; the excavating shovel of the vibrating harvesting device picks up the mixture of Ligusticum wallichii and soil and enters the vibrating mechanism, which separates the mixture and throws it backward, so that Ligusticum wallichii is completely separated from the soil, and the phenomenon of soil clogging does not occur. Finally, Ligusticum wallichii falls to the ground through the conveying mechanism.

![Figure 1. Structure of segmented Ligusticum wallichii harvester.](image)

3. Design of key components of Ligusticum wallichii harvester

3.1 Design of crushing device

In order to determine the rotational speed of the lawn mower in the crushing device and ensure that the stems of Ligusticum wallichii can be crushed in the working process, the shear performance test is carried out on Ligusticum wallichii. The mature stems of Aoping Town, Pengzhou City are selected as samples. In order to ensure more accurate performance of Ligusticum wallichii, the water loss of the stems is minimized after collecting the stems of Ligusticum wallichii. The test samples are shown in Figure 2.

![Figure 2. Test samples of Ligusticum wallichii stalk.](image)

Test method: The electronic universal testing machine controlled by a microcomputer is selected as the test instrument, as shown in Figure 3, the two ends of the stems are fixed, and the stalk is cut with a knife, the cutting position is selected between two platycodon grandiflorum. Eight groups of experiments are done in the shear test, and the shear test data are as follows Table 1, the width and thickness are measured after flattening the stems of Ligusticum wallichii.
Figure 3. Electronic universal test device.

Table 1. Parameter Table of Ligusticum wallichii Stem Shear Test.

| Serial number | Thickness (mm) | Width (mm) | Cross sectional area | Shear force | Shear strength |
|---------------|----------------|------------|----------------------|-------------|---------------|
| 1             | 2.37           | 10.91      | 25.86                | 44.7        | 1.73          |
| 2             | 2.61           | 10.75      | 28.06                | 42.9        | 1.53          |
| 3             | 1.94           | 9.55       | 18.53                | 29.1        | 1.57          |
| 4             | 2.62           | 9.64       | 25.26                | 44.4        | 1.76          |
| 5             | 2.49           | 8.87       | 22.09                | 35.5        | 1.61          |
| 6             | 2.43           | 9.17       | 22.28                | 36.2        | 1.62          |
| 7             | 1.99           | 9.85       | 19.60                | 32.7        | 1.67          |
| 8             | 2.01           | 9.71       | 19.52                | 32.3        | 1.65          |

According to the data in Table 1, the relationship between cross-sectional area of Ligusticum wallichii stem and shear force is plotted, as shown in Figure 4, it is concluded that the larger the cross-sectional area, that is, the larger the stalk, the greater the shear force.

Figure 4. Relationship between cross-sectional area of stem and shear force.

Through the data collection of Ligusticum wallichii stem at Ligusticum wallichii base in Aoping Town, Pengzhou City, the cross-sectional area of Ligusticum wallichii stem is about 22~28 mm², and the corresponding shear force is 40 N in Figure 4, so when calculating the rotational speed of the cutting head, the shear force is set to 40 N, and the rotational speed is calculated according to Formula (1).

\[ v = \frac{F \rho}{m} \]  

Where: \( v \)—the rotational speed of the mowing head, r/s; \( \rho \)—turning radius of straw rope, 0.23 m; \( m \)—the average weight of a single straw rope, \( 2.2 \times 10^{-3} \) kg; \( F \)—tangential force, N.

The rotational speed 3880r/min is obtained. The crushing device uses hydraulic oil provided by tractor as the power source, and adopts two-stage speed increase. Finally, the power is transmitted to the mowing head by T-shaped reducer, so that the mowing head rotates at high speed. The designed crushing device is shown in Figure 5.

Figure 5. Physical drawing of crushing device.
3.2 Vibration mechanism design

The vibration mechanism must have a good effect on soil breaking and separation, and avoid the phenomenon of soil clogging during work, so the vibration mechanism must also have the function of throwing the mixture backward. Referring to the design of rice vibration mechanism\[6\], the structure of the mechanism is preliminarily determined to be mainly composed of: Axis, crank, driving connecting rod, driven connecting rod, fixed connecting rod, bearing seat, side plate, vibrating plate and steel bar, as shown in Figure 6 show. The closed vector method is used to analyze the kinematics of the vibrating mechanism. Figure 7 is the motion analysis diagram of the vibrating mechanism. A rectangular coordinate system with O point as the origin of coordinates is established. The X and Y directions are as shown in the figure. Let the counterclockwise rotation of the OA connecting rod be the positive direction, and the angle between the crank and X negative direction be $\delta$. OA is a crank with a length of 50 mm; AB is the driving connecting rod with a length of 420 mm; BD is a fixed connecting rod with a length of 240 mm; BC and DE are driven connecting rods with a length of 200 mm, OC length of 500 mm, and the rotational speed of the axis is 240 r/min.

Let $l_1$, $l_2$, $l_3$, and $l_4$ be vectors of bars $OA$, $AB$, $CB$ and $OC$, and $\varphi_1$, $\varphi_2$, $\varphi_3$ and $\varphi_4$ are the angular displacements of rods $OA$, $AB$, $BC$ and $OC$ to the positive $X$ direction, where $l_1$, $l_2$, $l_3$, and $l_4$ are constants, and the complex vector form between them is:

$$l_1e^{i\varphi_1} + l_2e^{i\varphi_2} = l_3e^{i\varphi_3} + l_4e^{i\varphi_4}$$

Use Euler formula to simplify formula (2) to get angular displacements $\varphi_2$ and $\varphi_3$, and get formula (3).

$$\begin{align*}
\varphi_2 &= \arctan \frac{B + l_4}{A + l_3 \cos \varphi_3} \\
\varphi_3 &= 2\arctan \frac{B + \sqrt{A^2 + B^2 - C^2}}{A - C}
\end{align*}$$

Figure 6. Vibration mechanism.

Figure 7. Motion analysis diagram of vibration mechanism.
Where:

\[ A = l_1 - l_2 \cos \varphi \]
\[ B = -l_1 \sin \varphi \]
\[ C = \frac{A^2 + B^2 + l_1^2 - l_2^2}{2l_1} \]

The equation (2) is simplified after the derivative of time \( t \), and the angular velocities of \( AB \) and \( BC \) rods \( \omega_2 \) and \( \omega_3 \) are obtained:

\[
\begin{align*}
\omega_2 &= -\omega_1 \frac{l_1 \sin (\varphi_2 - \varphi_1)}{l_2 \sin (\varphi_2 - \varphi_1)} \\
\omega_3 &= \omega_1 \frac{l_1 \sin (\varphi_3 - \varphi_1)}{l_2 \sin (\varphi_3 - \varphi_1)}
\end{align*}
\]

Simplify the equation (2) for the second derivative of time \( t \) to obtain the acceleration of the \( AB \) rod:

\[ a_2 = \frac{l_2 \omega_2^2 - l_1 \omega_1^2 \cos (\varphi_2 - \varphi_1) - l_2 \omega_3^2 \cos (\varphi_3 - \varphi_1)}{l_2 \sin (\varphi_2 - \varphi_1)} \]  

In order to get the speed and acceleration of point \( B \), point \( F \) is introduced into \( AB \) bar, and vector \( F \) is perpendicular to \( AB \), so there is vector of, and the position vectors of point \( F \) are \( c \) and \( d \), which can be expressed by closed vector equation as follows:

\[ l_F = l_i e^{\omega_0 t} + ce^{\omega_0 t} + de^{i(\omega_2 t + 90^\circ)} \]

Use equation (6) to derive time \( t \) twice, and the lengths of vectors \( c \) and \( d \) are \( l_2 \) and \( 0 \), the velocity \( (v_Bx, v_By) \), and acceleration \( (a_Bx, a_By) \) of point \( B \) are obtained respectively.

\[
\begin{align*}
\omega_2 &= -\omega_1 \frac{l_1 \sin (\varphi_1 - \varphi_2)}{l_2 \sin (\varphi_1 - \varphi_2)} \\
\omega_3 &= \omega_1 \frac{l_1 \sin (\varphi_1 - \varphi_3)}{l_2 \sin (\varphi_1 - \varphi_3)} \\
a_{Bx} &= -(\alpha \omega_1 \cos \varphi_1 + \omega_2 l_1 \sin \varphi_1 + \omega_3 l_1 \cos \varphi_1) + \omega_1^2 l_1 \cos \varphi_1 \\
a_{By} &= -\omega_1 l_1 \sin \varphi_1 + \omega_2 l_1 \cos \varphi_1 - \omega_3 l_1 \sin \varphi_1
\end{align*}
\]

The steel bar is connected to the fixed connecting rod \( BD \) through vibrating plates and side plates, so the displacement of the steel bar is equal to that of the fixed connecting rod \( BD \), and the displacement of the steel bar is equal to that of point \( B \), \( v_B \) and \( a_B \) after the derivative of the displacement are also consistent with the velocity and acceleration on the steel bar, so the acceleration at \( a_B \) certain point on the steel bar is equivalent to that at point \( B \). When the mixture reaches the equilibrium limit position on the steel bar, the inertia force \( F_a \) acting on the mixture has two directions. When the steel bar accelerates to the right (negative \( X \) direction), the inertia force moves to positive \( X \) direction, and the mixture tends to slide forward along the inclined plane of the steel bar. When that steel bar is accelerate and displaced to the left (positive \( X \) direction), the inertial force is in negative \( X \) direction, and the mixture tend to slide backward along the inclined plane of the steel bar. And the angle between steel bar and horizontal plane is \( \alpha \) (25°), \( \beta \) is the angle between the inertial force \( F_a \) and \( X \) in the positive direction. Figure 8 shows the inertial force \( F_a \), gravity \( (mg) \), supporting force \( (N) \), and friction force \( (F) \) that the mixture receives on the inclined surface.

Figure 8 (a). Force diagram of the mixture sliding forward along the inclined plane.  
Figure 8 (b). Force diagram of mixture sliding backward along inclined plane.
Only when $F_a$ is above the inclined plane in Figure 8 can the mixture be thrown off the steel bar, i.e. $25^\circ \leq \beta \leq 205^\circ$, and the throwing off condition is obtained, as shown in formula (8).

\[
\begin{align*}
F_a \sin(\beta - \alpha) &\geq mg \cos \alpha, \quad (25^\circ \leq \beta \leq 115^\circ) \\
F_a \sin(180-\beta+\alpha) &\geq mg \cos \alpha, \quad (115^\circ \leq \beta \leq 180^\circ) \\
F_a \sin(\beta-180+\alpha) &\geq mg \cos \alpha, \quad (180^\circ \leq \beta \leq 205^\circ)
\end{align*}
\]

(8)

Bring in $l_1, l_2, l_3, l_4$ and $\alpha$, combining formula (8) and formula (7), when the mixture is thrown away, the value range of $\beta$ is: $45.2^\circ \leq \beta \leq 137.9^\circ$, from equation 3, when the mixture is thrown away, the value range of $\delta$ is: $22^\circ \leq \delta \leq 205^\circ$. According to formula (7), the velocity of the mixture when it is thrown away that: $v_x$ is $-47.75$ mm/s, $x_y$ is $-19.85$ mm/s. Assuming that the mixture falls on the steel bar again after $t$ time, the moving distances $s_x$ and $s_y$ of the steel bar in $X$ and $Y$ directions are respectively:

\[
\begin{align*}
\left\{ \begin{array}{l}
\quad s_x = \int_0^t \left( \alpha_1 l_1 \sin \varphi_1 + \alpha_2 l_2 \sin \varphi_2 \right) dt \\
\quad s_y = \int_0^t \left( \alpha_1 l_1 \cos \varphi_1 + \alpha_2 l_2 \cos \varphi_2 \right) dt
\end{array} \right.
\end{align*}
\]

(9)

The moving distances $L_x$ and $L_y$ of the mixture in $X$ and $Y$ directions in $t$ time are respectively:

\[
\begin{align*}
L_x &= v_x t \\
L_y &= 0.5g \left( t - \frac{v_y}{g} \right)^2 - \left( v_y - \frac{v_y}{g} - 0.5g \left( \frac{v_y}{g} \right)^2 \right)
\end{align*}
\]

(10)

Bringing in the parameters, the calculation shows that the mixture first contacts the steel in the $Y$ direction, and it is obtained that $t$ is 0.06944$s$, and the displacement $s_y$ of the steel in the $Y$ direction is 41.23 mm. After the mixture is thrown away, the distance $l_0$ moved backwards within $t$ is:

\[
l_0 = \frac{s_y}{\tan \alpha} = 88.42 mm
\]

Vibration mechanism is simplified and imported into Adams simulation software, refer to Figure 6 for the names of the parts in the simulation model. Set: the rotation speed of the crank is 4 r/s, the simulation time is 0.25 s, and the simulation steps are 50. The obtained speed at point $B$ is shown in Figure 9, and the acceleration is shown in Figure 10. When the crank turns 22$^\circ$, the corresponding time is 0.015 s, and the corresponding speed at this time that $v_x$ is $-45.76$ (mm/s) and $v_y$ is $-20.81$ (mm/s). The velocity obtained by the simulation is not much different from the velocity of the mixture throwing calculated by the motion analysis. It can be seen from Figure 10 that the steel bar is at the moment of maximum positive acceleration at this time, the accuracy of the throwing conditions is verified, indicating that the mixture can be thrown away, the vibration harvesting device will not occur the phenomenon of soil clogging.

Figure 9. Change of velocity at point B with time.
Figure 10. Change of acceleration at point B with time.

4. Prototype test
The experiment was conducted from May 10th, 2021 to May 12th, 2021; venue: Aoping Town, Chengdu City, Sichuan Province, China; test method: according to NY/T 3481-2019[7].

Table 2. Performance index requirements of medicinal material harvester.

| Serial number | Project      | Performance index |
|---------------|--------------|-------------------|
| 1             | Obvious rate.| ≧ 90%             |
| 2             | Loss rate    | ≦ 5%              |
| 3             | Damage rate  | ≦ 7%              |

4.1. Crushing device test
The test site of crushing the sample of the device is shown in Figure 11, and the measured rotational speed is shown in Figure 12. The crushing device can work normally, and the measured rotational speed is 4020 r/min.

Figure 11. Test site of crushing device.

Figure 12. Speed measurement site.

4.2. Vibration harvester test
Before working, adjust the rotational speed of the tractor rear output shaft according to the transmission ratio, so that the rotational speed of the shaft of the vibrating mechanism reaches 240 r/min. The test site of the vibrating harvester is shown in Figure 13.
Figure 13. Test site of vibration harvester.

Measuring three ridges in the experimental site with a working area of 19 m², collecting the experimental data for each ridge, and bagging Ligusticum wallichii according to the classification of surface, burial, damage and leakage, and weighing it. The mass per unit area is 1.76 kg/m², and the recorded values are shown in Table 3.

Table 3. Ligusticum wallichii test data collection table.

| Serial number | Surface mass W (kg) | Buried mass Z (kg) | Damage mass W₁ (kg) | Leakage quality Q (kg) | Theoretical total mass qB (kg) | Total mass W₀ (kg) |
|---------------|---------------------|--------------------|---------------------|-----------------------|-------------------------------|-------------------|
| 1             | 27.6                | 1.4                | 0.1                 | 0.2                   | 33.5                          | 29.3              |
| 2             | 27.5                | 1.4                | 0.2                 | 0.2                   | 33.5                          | 29.3              |
| 3             | 27.8                | 1.3                | 0.1                 | 0.1                   | 33.5                          | 29.3              |

According to the formula in the national standard NY/T 3481-2019, the calculated value is shown in Table 4. From the table, it can be concluded that the rate of obvious is about 95%, the rate of loss is about 4.5%, and the rate of damage is about 0.4%, all of which meet the performance requirements of the national standard for the medicinal material harvester. From the experimental results and data, there is no phenomenon of soil clogging in the harvesting process, the mixture can be thrown backwards by the vibrating mechanism.

Table 4. Ligusticum wallichii of Chuanxiong test data.

| Serial number | Obvious rate | Loss rate | Damage rate |
|---------------|-------------|-----------|-------------|
| 1             | 95.2%       | 4.8%      | 0.3%        |
| 2             | 95.1%       | 4.8%      | 0.6%        |
| 3             | 95.5%       | 4.2%      | 0.3%        |

5. Conclusion

(1) According to the test, the shear force of Ligusticum wallichii is 40 N, the minimum rotational speed of the crushing device is calculated to be 3880 r/min, and the rotational speed measured by the test is 4020 r/min, which can crush the stems of Ligusticum wallichii during the test.

(2) Kinematics analysis of the vibrating mechanism shows that when the crank angle of the vibrating mechanism is 22°, the mixture is thrown away, and the throw away distance is 88.42 mm.

(3) The experimental method in the standard NY/T 3481-2019 is used to test the harvesting device, and it is found that the obvious rate, loss rate and damage rate of the vibrating harvesting device are 95%, 4.5% and 0.4%, and there is no soil clogging phenomenon during the test. The accuracy of vibration mechanism design and kinematic analysis is verified, and the prototype met the harvesting requirements of Ligusticum wallichii.

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References

[1] Peng Fang, Chen Yuanyuan, Tao Shan, Yuan Can, Wu Yu, Shi Tiantian, Sha Xiufen, Liao Xuemei, Juck Zhang. Investigation and evaluation on the cultivation status of Chuanxiong in Sichuan Province [J]. Chinese journal of experimental traditional medical formulae, 2020, 26(02): 181-189.

[2] Liu Yu, Jiang Huixia, Luo Jun, Guo Jia, Wang Yipeng. Current situation and suggestions of mechanized production of Chuanxiong in shifang city [J]. Modern Agricultural Science and Technology, 2021: 145-146+150.

[3] Liu Xiaofeng, Yu Zhang. Mechanized operation technology of Chinese herbal medicines [J]. Agricultural Mechanization and Electrification, 2006(05): 47-48.

[4] Zhang Zhaoguo, Du Zonglin, Cui Zhenmeng, Liu Weijian, Ray Dylan. Kinematics analysis and simulation test of digging and removing device of Sanqi harvester [J]. Journal of Kunming University of Science and Technology (Natural Science Edition), 2019, 44(03): 41-51.

[5] Fan kaixin. licorice harvester design and key mechanism simulation analysis [D]. Gansu agricultural university, 2018.

[6] Zhong Tang et al. Effects of Stem Cutting in Rice Harvesting by Combine Harvester Front Header Vibration[J]. Advances in Materials Science and Engineering, 2019.

[7] Shi Linxiang. NY/T 3481-2019, Technical Specification for Quality Evaluation of Rootstock Chinese Medicine Harvesters [S].