Design and experiment of vibration plate type camellia fruit picking machine

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Abstract: In order to solve the problem of high missed rate of camellia fruits and high damage rate of flower buds during vibratory picking, through the study on the biological characteristics of camellia tree, the crown of camellia tree was divided into upper and lower canopy at the maximum canopy diameter. A kind of vibration plate type camellia fruit picking machine was designed. The structure and working principle of the whole machine were described. Through the analysis of the factors of camellia fruit abscission, it is concluded that frequency, amplitude and working time are the main factors affecting the magnitude of inertia force. Through preliminary research and coupling simulation, the horizontal range of each factor is determined: operation time is 5 s, 10 s, 15 s, frequency is 3 Hz, 5 Hz, 7 Hz and amplitude is 50 mm, 60 mm, 70 mm. Orthogonal tests were carried out on the upper and lower canopies successively, and the comprehensive scoring method was used to analyze the orthogonal test results. The results showed that the optimal combination of working parameters for picking camellia in the upper canopy was $A_3B_3C_2$, that is, the operation time was 15 s, the amplitude was 70 mm and the frequency was 5 Hz. Under this condition, the missed picking rate of camellia fruits was 8.21% and the rate of flower buds damage was 9.12%. The optimal combination of working parameters for picking camellia fruits in the lower canopy was $A_3B_1C_3$, that is, the operation time was 15 s, the amplitude was 50 mm and the frequency was 7 Hz. Under this condition, the rate of missing picking of camellia fruits was 6.84% and the rate of flower buds damage was 6.92%.

Keywords: canopy stratification, structural design, analysis of shedding factors, coupling simulation, orthogonal test
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1 Introduction

Camellia tree is a characteristic oil crop in China and one of the four largest woody oil crops in the world[1]. There are long history of cultivation, wide distribution area, large planting area, and multiple uses[2]. Camellia oil is rich in nutrients and good oil quality, it is deeply loved by the people and enjoys the reputation of "Oriental Olive Oil"[3]. Camellia oil is easily absorbed and digested by the body, which is great for preventing arteriosclerosis and treating hypertension[4]. Tea oil can also be made into lubricating oil, tea cakes, soap, etc. It plays an important role in agriculture, chemical industry and light industry[5]. At present, camellia fruits mainly rely on manual picking, which requires a large amount of labor and extremely low efficiency[6]. Due to the lack of labor, the manual picking method of camellia fruit has become the weakest link in the development of the camellia oil industry, which hinders the rapid development of the camellia oil industry seriously[7].

In order to improve the recovery rate of forest fruits and reduce the damage rate of forest fruits, a large number of studies abroad have been carried out on the vibration harvesting of citrus, olive, coffee beans, blueberries, pistachios, etc. The results showed that the picking method by applying vibration to fruits has better effect[8-15]. The biological characteristics of flower and fruit grow synchronously is the biggest challenge in the process of mechanization of camellia fruit picking. Domestic research on the camellia fruit vibration picking machinery started late, but a variety of vibration type camellia fruit harvesting equipment has also been designed. Gao et al.[16] designed a suspension vibration type camellia fruit picking machine, by applying mechanical vibration to the trunk, when the inertial force generated by the movement of the fruit is greater than the binding force of the stalk, the fruit will fall from the camellia fruit tree. The harvesting efficiency of the device is very high, but the vibration causes great damage to the tree body. Wang et al.[17] designed a vibrating camellia green fruit harvester by analyzing the topography of the camellia fruit planting area and the characteristics of the camellia plant. The crank-connecting rod mechanism was used to drive the picking head to make reciprocating linear motion, thus generating vibration excitation force on the trunk, this method also produces greater damage to the *Camellia oleifera* tree. Li et al.[18] designed a canopy vibration flapping device for camellia fruit, which uses a vibrator to drive the flapping rod to vibrate the entire canopy. Although the camellia fruit has a high picking efficiency, the

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canopy branches and flower buds have larger damaged. Wu et al.[19] designed a shaking branch type camellia fruit picking machine, which uses clamping claw to clamp a single branch and then excites it, the fruit missed rate and flower bud damage rate are low, however, for single branch operations, the picking efficiency must be decreased.

The above studies showed that most of the vibration picking devices developed at present vibrate the trunk, branches or the whole tree canopy, and there is no device for layered vibration harvesting of camellia tree canopy. Gupta et al.[20,21] divided the citrus canopy into top, middle and bottom regions and used three sets of vibration parameters applied to each of the three regions of the citrus canopy. This approach substantially reduced damage to canopy branches during citrus harvesting. Pu et al.[22] divided the citrus canopy into two parts, the top and the bottom, using different frequencies adapted to the different areas of the canopy. This approach obtained lower backward branch damage and higher fruit removal rates. Drawing on the experience of stratified harvesting of citrus, the crown of camellia tree was divided into upper and lower canopy at the maximum canopy diameter to reduce camellia fruit missed rate and bud damage rate during vibratory picking.

The main purpose of this paper is to analyze the effect of layered vibratory picking on camellia fruit missed rate and bud damage rate. The design of the key components of the machine and the analysis of the shedding factors of the camellia fruit were mainly carried out, and through simulation analysis and field trials, better operating parameters for the upper and lower canopy of camellia tree were obtained, which provided a reference for the design of vibration picking device of camellia fruit.

2 Materials and methods

2.1 Biological characteristics of camellia trees

18 camellia trees were randomly selected from 6 years old “Changlin 4”, “Changlin 40”, “Changlin 53”, with row spacing of 4 m and plant spacing of 2.5 m. The measurement of tree crown is shown in Figure 1, and the measurement parameters of tree crown are listed in Table 1. The dimension *d* between the peripheries of two adjacent tree crowns provides reference for the size design of the picker. The thickness *w*' of the surface layer of the canopy determines the size of the vibration plate, the tree height *H* and the trunk height *h* put forward requirements for the picking height range of the picking device.

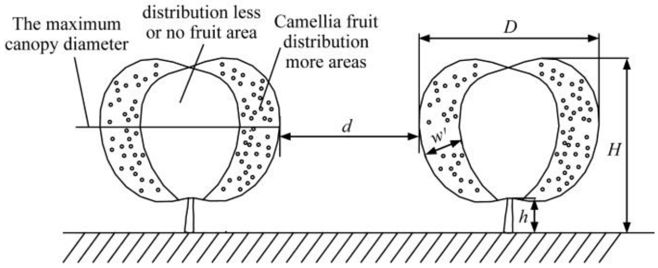


Figure 1 Schematic diagram of tree size

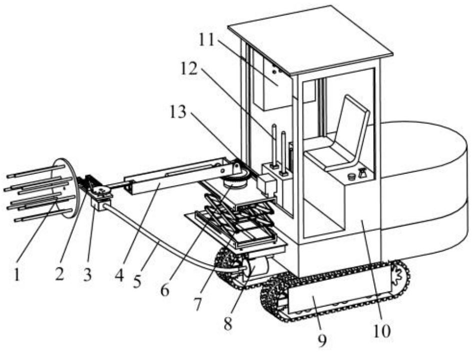
Table 1 Crown parameter measurement (m)

Parameters	Measurement range	Average value
d	1.71-2.14	1.89
D	1.83-2.53	2.21
H	1.75-2.66	2.25
h	0.35-0.58	0.40
w'	0.30-0.65	0.50

The number of camellia fruits in multiple tree crowns was counted, and it was found that camellia fruits were mainly distributed in the canopy surface of 0-500 mm[23]. From the perspective of vertical distribution of camellia fruits, the distribution of camellia fruits in the bottom and the top regions was relatively small, the reason may be that there was little light at the bottom of the canopy, which affected the differentiation of flower buds, and the vegetative growth of shoots at the top of the canopy was stronger than the reproductive growth[24]. Therefore, the middle region has a larger proportion of camellia fruit in the canopy, which is the priority area for mechanical harvesting. At the maximum canopy diameter in the middle region, the canopy was divided into the upper and lower canopy.

2.2 Machine structure and working principle

According to the research on the growth environment and tree characteristics of the camellia forest, the overall structure of the picking machine is shown in Figure 2. It is mainly composed of hydraulic rotating chassis, cab, lifting platform, telescopic boom, rack and pinion mechanism, telescopic arm, vibration mechanism, vibration plate and electronic control system, etc. The rack and pinion mechanism, the lifting platform and the telescopic boom are all adjusted by hydraulic cylinder, the return oil pipe and the pressure oil pipe of the hydraulic cylinder are connected with the hydraulic circuit of the hydraulic rotating chassis.



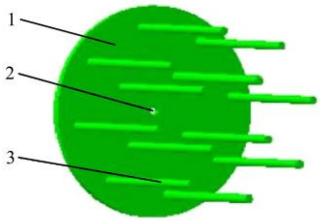
1. Vibration plate 2. Vibration mechanism 3. Reducer 4. Telescopic boom 5. Soft shaft 6. Rotating base 7. Lifting platform 8. Motor 9. Hydraulic rotating chassis 10. Cab 11. Electric control box 12. Hydraulic joystick 13. Rack and pinion mechanism

Figure 2 Structure of picking machine

At the beginning of the work, drive the picker close to the camellia tree woodland to work on the camellia trees on both sides. The rotating chassis of the picker can greatly and quickly adjust the operating angle of the vibration plate. The rack and pinion mechanism can fine-tune the operating angle of the vibration plate. Ensure the vibration plate is inserted into the canopy from the appropriate position by operating the hydraulic joystick to adjust the height of the lifting platform and the length of the telescopic boom. The electric control box controls the start, stop and speed of the motor, starts the motor, the motor power passes through the soft shaft and then passes through the reducer to drive the vibration mechanism to operate. The vibration mechanism converts the rotational motion into the linear reciprocating motion which is required by picking camellia fruit. The vibration plate generates an exciting force to act on the canopy branches, causing the camellia fruit to vibrate along with the branches. When the inertia force is greater than the binding force of the fruit stalk, the camellia fruit will fall off from the branches, then to achieve the purpose of the canopy fruit picking.

2.3 Design of vibration plate

Vibration plate is one of the important structure of the picking device, main structure as shown in Figure 3. Vibration plate is composed of the circular plate and vibration rods, the circular plate center opened a 20 mm diameter thread hole connected with the slide bar. In order to reduce vibration damage in canopy branches and flower buds, the circular plate and vibration rods are made of nylon material with good toughness and high bending strength to prevent damage to the tree body when inserted into the canopy. The density and elastic modulus of canopy branches are 1.345 g/cm^3 and 3000 MPa respectively, while the density and elastic modulus of nylon are 1.140 g/cm^3 and 2830 MPa[25]. They are relatively close to each other. According to the research and test conducted by the subject group[26], the vibrating rod with a diameter of 20 mm was chosen to have the ability to vibrate the canopy of the camellia tree.



1. Circular plate 2. Thread hole 3. Vibration rods

Figure 3 Structure of vibration plate

The design of the vibration plate should be based on the characteristics of the tree crown branches. As known above, the diameter of the tree crown is about 2200 mm. Considering that the mass of the vibration plate is too large, it will lead to the overload of the front end of the picking machine, and the size of the circular plate is not too large, the design diameter of the circular plate is 500 mm, and the vibration rods are regularly distributed on the vibration plate, so as to realize the operation of the secondary branches in the canopy. Since camellia fruits are mainly distributed in the canopy surface of 0-500 mm, the length of the vibration rod is 550 mm, which can meet the requirements of picking camellia fruits in the canopy of the operation side. Considering the stiffness of the vibration rod, the diameter of the vibration rod is 20 mm.

The distribution of vibration rods on the circular plate will seriously affect the harvest of camellia fruit. The excessive spacing of elastic vibration rods will lead to a great loss of energy transfer between elastic vibration rods and branches, which cannot guarantee the harvest of camellia fruit. The spacing is too small, which will affect the insertion of vibration rods into the canopy. Therefore, reasonable distribution of vibration rods becomes particularly important. Since the initial diameter of the secondary branches is 35.27-49.72 mm, and the angle between most secondary branches and the vertical direction is 23°-45°, four vibration rods are uniformly distributed on a circle with a diameter of 200 mm, 8 vibrating rods are uniformly distributed on a circle with a diameter of 400 mm, as shown in Figure 4.

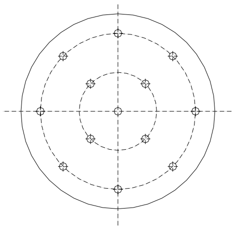
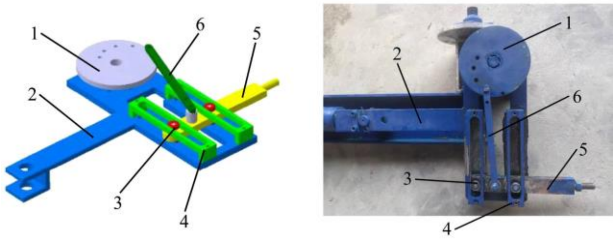


Figure 4 Distribution of the vibrating rods

2.4 Design of vibration mechanism

The vibration mechanism is composed of Rotating disc, connecting rod, slide block, slide bar, press plate and support plate, the structure is shown in Figure 5. Both the press plate and the support plate are provided with oval slide rail grooves, and the slide bar is connected to the slide block by a pin, slide on the oval slide rail grooves of the pressure plate and the support plate, the slide bar and the vibration plate are connected by threads, the vibration mechanism converts the kinetic energy of the motor into periodic excitation force, and the eccentric hole plays the role of adjusting the amplitude.



1. Rotating disc 2. Support plate 3. Slide block 4. Press plate 5. Slide bar 6. Connecting rod

Figure 5 The excitation mechanism

The eccentric distance of the design eccentric hole is 40 mm, 50 mm, 60 mm, 70 mm and 80 mm respectively, then the diameter of the rotating disc is 170 mm. As the maximum eccentric distance of the eccentric hole is 80 mm, then the travel of the slide bar is 160 mm. In order to meet the travel of the slide bar and at the same time prevent the slide bar from colliding with the two ends of the press plate, the length of the slide rail slot is 186 mm. Considering that the slide bar will have a large friction with the support plate during the sliding process, choose 4 sliders (outer diameter of 24 mm, inner diameter of 8 mm, thickness of 8 mm), then the slideway slot width is 24 mm and thickness is 8 mm.

2.5 Analysis of factors of camellia fruit abscission

2.5.1 Harvesting dynamic model

The vibration mechanism and the vibration plate can be simplified to a crank slider mechanism, as shown in Figure 6. This mechanism converts the rotary motion of the power equipment into the linear reciprocating motion, and the simple harmonic force generated by the reciprocating motion of the vibration plate can be used as exciting force of camellia fruit picking.

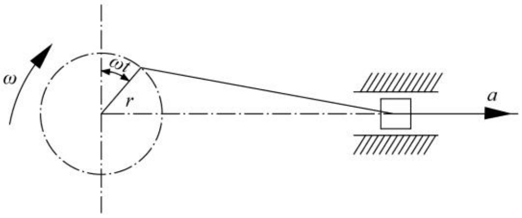


Figure 6 Slider-crank mechanism

The displacement of the vibration plate in the horizontal direction:

$$x = r\sin\omega t \tag{1}$$

The speed and acceleration of vibration plate:

$$v = \omega r\cos\omega t \tag{2}$$

$$a = -\omega^2 r\sin\omega t \tag{3}$$

The reciprocating excitation force generated by the vibration plate:

$$F = ma = -mr\omega^2\sin\omega t \tag{4}$$

where, r is the eccentricity, m; a is the acceleration of reciprocating motion, m/s^2; ω is the angular velocity of the disk, rad/s; m is the mass of the vibration plate; kg.

The excitation force generated by the vibration plate acts on the canopy branches, since the branches are only excited by the reciprocating motion of the vibration plates, only the system degree of freedom that is consistent with the direction of the reciprocating excitation force are considered for simplifying the vibration model[27], the picking kinetic model of the vibration plate-secondary branch is shown in Figure 7.

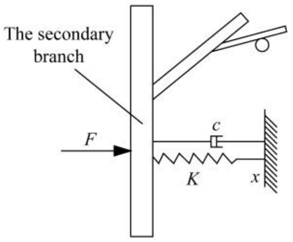


Figure 7 Harvesting dynamic model

System kinetic energy:

$$T=\frac{1}{2}M\dot{x}^2 \tag{5}$$

System potential:

$$V=\frac{1}{2}Kx^2 \tag{6}$$

Lagrangian function:

$$L=T-V=\frac{1}{2}M\dot{x}^2-\frac{1}{2}Kx^2 \tag{7}$$

where, T is the system kinetic energy, J; V is the system potential, J; L is the Lagrangian quantity; M is the total mass of the vibration plate and branches, kg; x is the system speed, m/s; K is the stiffness coefficient, N/m.

System resistance:

$$D=\frac{1}{2}c\dot{x}^2 \tag{8}$$

where, D is the Rayleigh dissipation function; c is the system equivalent viscous damping coefficient, N s/m.

In order to analyze the dynamic characteristics of the system, Lagrange's second-kind dynamic equation is introduced:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{x}}\right)+\frac{\partial D}{\partial \dot{x}}-\frac{\partial L}{\partial x}=F \tag{9}$$

Substituting Equations (4), (7) and (8) into Equation (9), the vibration differential equation of the second-order branch can be obtained as:

$$M\ddot{x}+c\dot{x}+Kx=-m\omega^2 l\sin\omega t \tag{10}$$

From the vibration theory, the vibration displacement equation of the secondary branch is:

$$x=-A\sin(\omega t-\varphi) \tag{11}$$

where, A is the amplitude of the steady-state response, mm; φ is phase angle, (°).

Substituting Equation (11) into Equation (10), the steady-state response of the system is solved as:

$$A=\frac{m\omega^2 l}{\sqrt{(K-M\omega^2)^2+(c\omega)^2}} \tag{12}$$

$$\varphi=\arctan\frac{c\omega}{K-M\omega^2} \tag{13}$$

2.5.2 Analysis of the inertial force of the fruit

After the branches are subjected to periodic external force, the vibration is transmitted to the camellia fruit. In the dynamic model of the sessile fruit, when the excitation mechanism exerts a vibration inertia force on the branches, the camellia fruits and the branches have the same vibration law, due to the branches that in the vertical direction have slight vibration, so only the vibration of the *Camellia oleifera* fruit in the horizontal position needs to be considered[28,29], that is, the vibration displacement x_0 of the camellia fruit is

$$x_0=-A\sin(\omega t-\varphi) \tag{14}$$

Camellia fruit is mainly affected by its own gravity G, the binding force of the stalk F_3, and the inertial force F_4, as shown in Figure 8. To separate the fruit from the branch, it is necessary to satisfy that the combined force of the inertial force and the fruit gravity is greater than the binding force of the stalk. Due to the low gravity of the camellia fruit, under the forced vibration, the fruit will fall off mainly by inertial force.

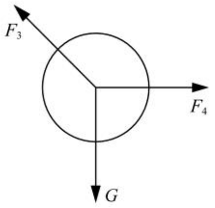


Figure 8 Schematic diagram of fruit stress

The inertial force of camellia oleifera fruit is:

$$\begin{aligned}F_4&=m_0\ddot{x}_0=m_0A\omega^2\sin(\omega t-\varphi)\\&=\frac{m_0m\omega^4 l}{\sqrt{(K-M\omega^2)^2+(c\omega)^2}}\sin\left(\omega t-\arctan\frac{c\omega}{K-M\omega^2}\right)\end{aligned} \tag{15}$$

where, m_0 is the quality of a single camellia fruit, kg.

From the above formula, frequency and amplitude are the main factors that affect the magnitude of inertial force. The greater frequency and amplitude, the greater the inertial force, the easier the camellia fruit will fall off, and the higher the recovery ratio; if the amplitude is too large, although the recovery rate is high, it will cause greater damage to the branches and flower buds. If the frequency and amplitude are too small, the excitation effect will be poor. Therefore, it is particularly important to select the appropriate amplitude and frequency for picking camellia fruit. In the actual vibration harvesting of forest fruit, the operation time also affects the fruit abscission[30,31]. Therefore, the operation time is taken as another factor affecting the camellia fruit abscission.

2.6 Vibration simulation analysis based on ADAMS

In order to further analyze the response characteristics of camellia branches and verify the correctness of the dynamic model and the rationality of the picking device, the rigid-flexible coupling simulation of the vibration system was carried out based on ADAMS.

The trunk, secondary branch, tertiary branch and quaternary fruit-bearing branch of camellia tree are clearly subordinate. In order to simplify the model, the tertiary branch and quaternary branch are ignored in the process of tree modeling, and only the secondary branch is modeled. 18 camellia trees were randomly selected to make statistics on the number, length, beginning and end diameter of the secondary branches and the angle between the secondary branches and the vertical direction of each tree. The results showed that each tree had 2 to 4 secondary branches, the length of secondary branches is 86.1-134.5 cm, the beginning diameter of secondary branches is 34.58-49.72 mm, and the ending diameter of secondary branches is 15.24-32.46 mm. The angle between most secondary branches and the vertical direction is 23°-45°. The angle between a few secondary branches and the vertical direction is between 0°-10° and 75°-85°. According to the statistical results, the parameters of secondary branches were simplified, as shown in Table 2.

Table 2 Simplified parameter of secondary branch

No.	The length of the second branch/cm	Diameter at the beginning of the second branch/mm	Diameter at the beginning of the second branch/mm	The Angle of the second branch to the vertical direction/(°)
1	130	45	26	40
2	140	40	24	30.
3	100	34	22	4
4	90	36	20	80

The parameters of the secondary branch above were used to establish a 3D model of camellia tree in SolidWorks and imported into ADAMS. Considering the deformation of camellia tree in the vibration process, and in order to ensure the accuracy of simulation, camellia tree body needs flexible processing. In this paper, the flexible MNF file of camellia tree body is established in ADAMS /View by using the Auto /Flex module in ADAMS to replace the rigid camellia tree body that is established in SolidWorks. The material of the excitation mechanism is steel, and the material of the vibration plate is nylon. A review of the literature shows that the material properties of the components are shown in Table 3.

Table 3 Material parameter table

Materials	Density/g·cm^{-3}	Elastic modulus /MPa	Poisson's ratio
Branch	1.345	3000	0.17
Vibration plate	1.140	2830	0.4
Vibration mechanism	7.850	2.5×10^5	0.3

The coupling model of vibration device and flexible camellia tree was established, and the midpoint of the second branch was selected as the detection point, as shown in Figure 9, After constraints, motion and material properties were set, the simulation time was set to 5s and the number of steps was set to 50.

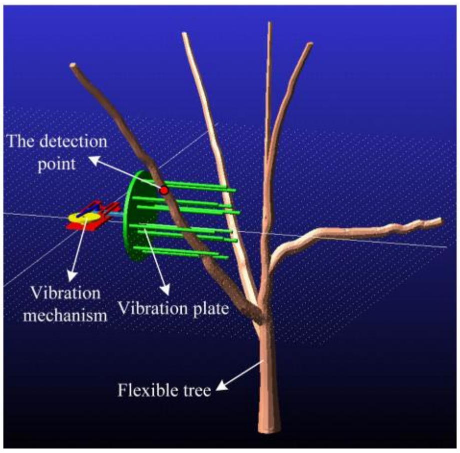


Figure 9 The coupling fruit tree model

2.7 Field harvesting test

Camellia fruit picking test was carried out in the camellia forest base in Yongzhou city, Hunan province in October 2020 (Figure 10). The soil of the test site is red loam, which can be used for the normal operation of the picking machine. The test materials are the 6-year-old camellia trees with varieties of Changlin 4, Changlin 40 and Changlin 53. 18 camellia trees of equal growth were selected to stratify the upper and lower canopies at the maximum diameter of the canopy. 9 trees were selected as a group for the upper canopy picking trial and the remaining 9 trees were selected as another group for the lower canopy picking trial. The main operating parameters of the camellia fruit picking machine are shown in Table 4.

Table 4 Main operating parameters of picking machine

Main operating parameters	Parameter values
Supporting power of the whole machine/kW	15
Dimensions (length×width×height)/mm×mm×mm	2800×1400×2200
Range of picking heights/mm	700-2700
Range of amplitude/mm	40, 50, 60, 70, 80
Range of vibration frequencies/Hz	0-10
Range of climbing angles/(°)	0-30

Figure 10 Test field of camellia fruit picking

Taking amplitude, frequency, operating time as test factors, camellia fruit missed rate and the flower bud damage rate as the evaluation index, three factors and three levels orthogonal test has carried out on the upper and lower canopy respectively, determine the optimal combination of each canopy operating parameters.

The formula of the camellia fruit missed rate is:

$$P=\frac{N_1}{N_2}\times100\% \tag{16}$$

where, P is missed rate of camellia fruit, %; N_1 is the number of camellia fruits that did not fall off after picking; N_2 is the total number of camellia fruit before picking.

The formula of flower bud damage rate is:

$$Q=\frac{N_4-N_3}{N_4}\times100\% \tag{17}$$

where, Q is the rate of flower bud damage, %; N_3 is the number of flower buds not falling off after picking; N_4 is the total number of flower buds before picking.

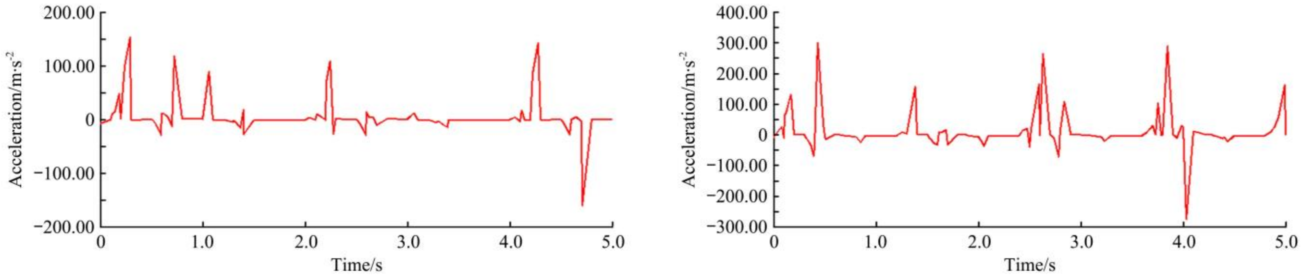
3 Results and discussion

3.1 Simulation results and analysis

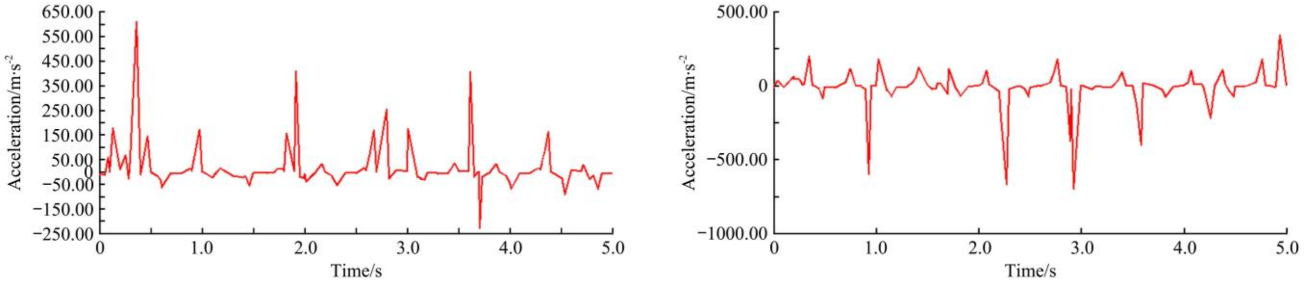
In this simulation, the lower position of the tree canopy is vibrated, and choose the midpoint of the secondary branch as the detection point. The initial amplitude of the simulation is set to 50 mm, and the rotating speed of the rotary table is 180 r/min, 300 r/min, 420 r/min and 540 r/min respectively, and the corresponding frequencies is 3 Hz, 5 Hz, 7 Hz and 9 Hz. The simulation results are shown in Figure 11.

As can be seen from Figure 11, when the amplitude is fixed at 50mm, the maximum acceleration of the detection point gradually increases with the increase of frequency, and the inertia force generated by camellia fruit is also greater, which makes the camellia fruit is easier to fall off. When the frequency reaches 7 Hz and then the vibration frequency is increased, the increase of the maximum acceleration at the detection point is not obvious, so the frequencies are selected as 3 Hz, 5 Hz and 7 Hz.

The fixed frequency is 5 Hz, and the amplitudes are set as 40 mm, 50 mm, 60 mm, 70 mm and 80 mm respectively, the simulation time is 5 s, and the simulation steps are 50. The simulation results are shown in Figure 12.

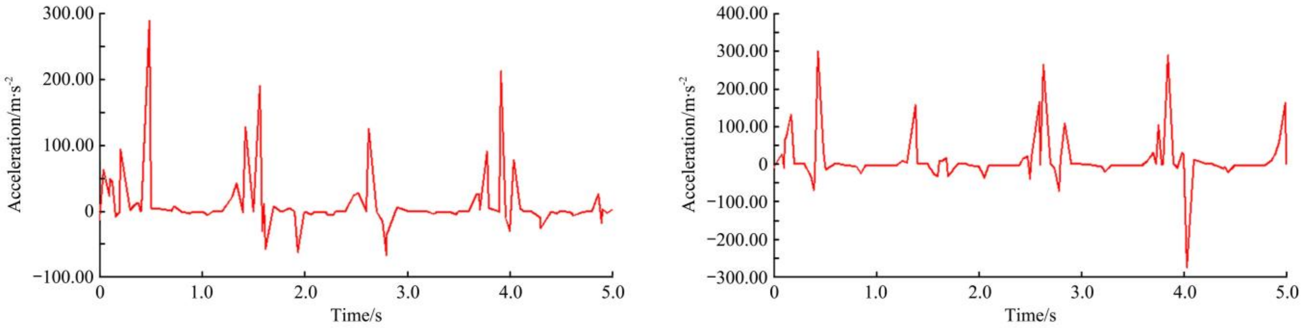


a. Frequency 3 Hz b. Frequency 5 Hz

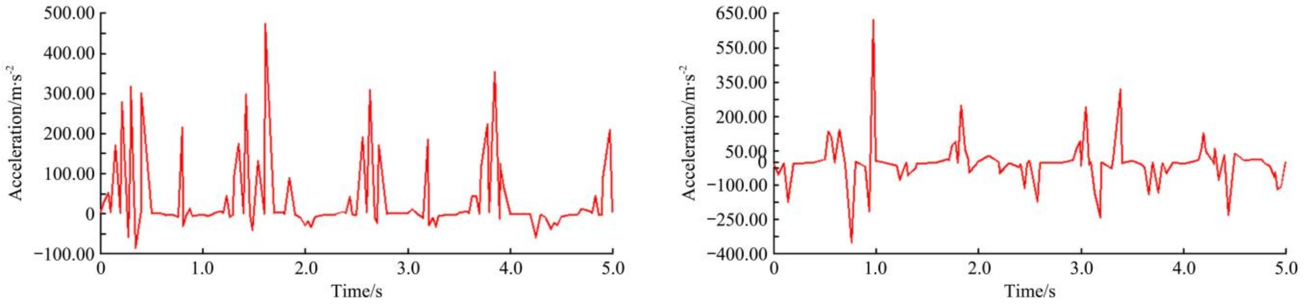


c. Frequency 7 Hz d. Frequency 9 Hz

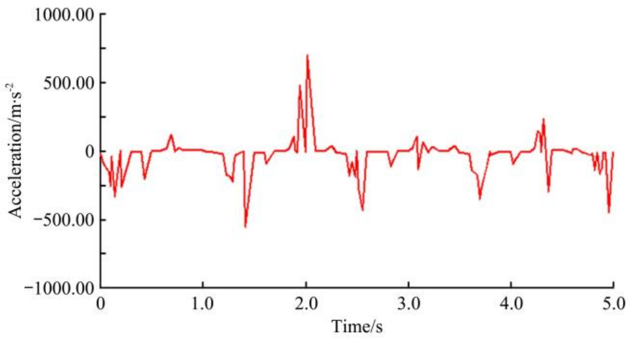
Figure 11 Accelerations in excitation directions of detection points under different frequencies



a. Amplitude 40 mm b. Amplitude 50 mm



c. Amplitude 60 mm d. Amplitude 70 mm



e. Amplitude 80 mm

Figure 12 Accelerations in excitation directions of detection points under different amplitudes

As can be seen from Figure 12, when the frequency is fixed at 5Hz, the maximum acceleration of the detection point gradually increases with the increase of the amplitude, and the inertia force generated by camellia fruit is also greater, so the camellia fruit is easier to fall off. However, the maximum acceleration of the detection point increases slowly when the amplitude increases from 70 mm to 80mm, so the amplitude are selected as 50 mm, 60 mm and 70 mm.

It can be seen from the above analysis that the acceleration of camellia branches under external excitation force increases with the increase of excitation frequency and amplitude, which is consistent with the conclusion of the picking dynamics model.

3.2 Experiment results and analysis

According to the preliminary test and simulation analysis in the early stage, the level values of each factor are determined. The level table of orthogonal test factors is shown in Table 5. The orthogonal test results and range analysis of upper and lower canopy are shown in Tables 6-9.

Table 5 Factors level table of orthogonal experiment

Level	Operating time *A*/s	Amplitude *B*/mm	Frequency *C*/Hz
1	5	50	3
2	10	60	5
3	15	70	7

Table 6 Results of orthogonal test of the upper canopy

No.	Operating time *A*/s	Amplitude *B*/mm	Frequency *C*/Hz	Missed rate *P*/%	Damage rate of flower bud *Q*/%
1	5	50	3	15.21	6.45
2	5	60	5	13.18	11.21
3	5	70	7	7.75	15.36
4	10	50	5	14.13	7.49
5	10	60	7	9.86	14.45
6	10	70	3	12.68	10.37
7	15	50	7	12.27	13.12
8	15	60	3	13.67	8.13
9	15	70	5	8.21	9.12

Table 7 Results of range analysis of the upper canopy

Index		*A*	*B*	*C*
Missed rate	k_1	12.05	13.87	13.85
	k_2	12.22	12.24	11.84
	k_3	11.38	9.55	9.96
	R	0.84	4.32	3.89
	Superior level	A_3	B_3	C_3
	Influence degree		*B*, *C*, *A*	
Damage rate of flower bud	k_1	11.01	9.02	8.32
	k_2	10.77	11.26	9.27
	k_3	10.12	11.62	14.31
	R	0.89	2.60	5.99
	Superior level	A_3	B_1	C_1
	Influence degree		*C*, *B*, *A*	

It can be seen from Table 7 that in the upper canopy, the order of various test factors influence the camellia fruit missed rate is: amplitude *B*, frequency *C*, operating time *A*, and the better combination of working parameters is $A_3B_3C_3$; the order of each test factor affects flower bud damage rate is: frequency *C*, amplitude *B*, operating time *A*, and the better working parameter combination is $A_3B_1C_1$.

Table 8 Results of orthogonal test of the lower canopy

No.	Operating time *A*/s	Amplitude *B*/mm	Frequency *C*/Hz	Missed Rate *P*/%	Damage rate of flowerbud *Q*/%
1	5	50	3	13.61	6.45
2	5	60	5	9.48	8.56
3	5	70	7	5.75	11.59
4	10	50	5	9.04	7.21
5	10	60	7	7.56	9.45
6	10	70	3	9.43	9.92
7	15	50	7	6.84	6.92
8	15	60	3	10.83	8.12
9	15	70	5	7.85	10.48

Table 9 Results of range analysis of the lower canopy

Index		*A*	*B*	*C*
Missed rate	k_1	9.61	9.83	11.29
	k_2	8.68	9.29	8.79
	k_3	8.51	7.68	6.72
	R	1.10	2.15	4.57
	Superior level	A_3	B_3	C_3
	Primary and secondary factors		*C*, *B*, *A*	
Damage rate of flower bud	k_1	8.87	6.86	8.16
	k_2	8.86	8.71	8.75
	k_3	8.51	10.66	9.32
	R	0.36	3.80	1.16
	Superior level	A_3	B_1	C_1
	Influence degree		*B*, *C*, *A*	

It can be seen from Table 9 that in the lower canopy, the order of various test factors influence the camellia fruit missed rate is: frequency *C*, amplitude *B*, operating time *A*, the better working parameter combination is $A_3B_3C_3$; the order of the each test factors effects the flower buds damage rate is: amplitude *B*, frequency *C*, operating time *A*, the better combination of working parameters is $A_3B_1C_1$.

Due to the inconsistency of the optimal parameter combinations for the camellia fruits missed rate and the flower bud damage rate, the orthogonal test results were analyzed by comprehensive scoring method. The calculation formula of the membership degree of camellia fruit missed rate u_1 and the membership degree of flower bud damage rate u_2 is:

$$U = \frac{S - S_{\min}}{S_{\max} - S_{\min}} \tag{18}$$

where, *U* is the index membership degree; *S* is the index value; $S_{\max}$ is the index maximum; $S_{\min}$ is the index minimum.

In actual harvesting, artificial harvesting will also cause damage to the flower buds. Therefore, the lower missed rate of camellia fruit were firstly ensured, and secondly to ensure the lower damage rate of the flower buds, select the weighting factor of the missed rate is 0.6, the weighting factor of the flower bud damage rate is 0.4, the comprehensive score results and range analysis are listed in Tables 10 and 11.

It can be seen from Table 10 that the order of each test factor effects the upper canopy comprehensive score is: amplitude *B*, frequency *C*, operating time *A*, and the better working parameter combination is $A_3B_3C_2$, that is, the operating time is 15 s, the amplitude is 70 mm, the frequency is 5 Hz, at this time, the camellia fruit missed rate is 8.21%, and the flower bud damage rate is 9.12%.

Table 10 Analysis results of comprehensive scores and range analysis of the upper canopy

No	*A*/s	*B*/mm	*C*/Hz	u_1	u_2	*u*
1	5	50	3	1	0	0.6000
2	5	60	5	0.7279	0.5342	0.6504
3	5	70	7	0	1	0.4000
4	10	50	5	0.8552	0.1167	0.5598
5	10	60	7	0.2828	0.8979	0.5289
6	10	70	3	0.6609	0.4400	0.5725
7	15	50	7	0.6059	0.7486	0.6630
8	15	60	3	0.7936	0.1886	0.5516
9	15	70	5	0.0617	0.2997	0.1569
Composite score			k_1	0.5501	0.6076	0.5747
			k_2	0.5537	0.5769	0.4557
			k_3	0.4571	0.3765	0.5306
			R	0.0966	0.2311	0.1190
			Superior level	A_3	B_3	C_2
			Influence degree		*B*, *C*, *A*	

It can be seen from Table 11 that order of the each test factor effects lower canopy comprehensive scores is: frequency *C*, amplitude *B*, operating time *A*, and the better working parameter combination is $A_3B_1C_3$, that is, the operating time is 15 s, the amplitude is 50 mm, the frequency is 7Hz, at this time, the missed rate of camellia fruit is 6.84%, and the flower bud damage rate is 6.92%.

Table 11 Analysis results of comprehensive scores and range analysis of the lower canopy

No	*A*/s	*B*/mm	*C*/Hz	u_1	u_2	*u*
1	5	50	3	1	0	0.6000
2	5	60	5	0.4746	0.4105	0.4489
3	5	70	7	0	1	0.4000
4	10	50	5	0.4186	0.1479	0.3103
5	10	60	7	0.2303	0.5837	0.3716
6	10	70	3	0.4682	0.6751	0.5510
7	15	50	7	0.1387	0.0914	0.1198
8	15	60	3	0.6463	0.3249	0.5177
9	15	70	5	0.2672	0.7840	0.4739
Composite score			k_1	0.4830	0.3434	0.5562
			k_2	0.4110	0.4461	0.4110
			k_3	0.3705	0.4750	0.2971
			R	0.1125	0.1316	0.2591
			Superior level	A_3	B_1	C_3
			Influence degree		*C*, *B*, *A*	

4 Conclusions

Through the study on the biological characteristics of camellia tree, the crown of camellia tree was divided into upper and lower canopy at the maximum canopy diameter. A kind of vibration plate type camellia fruit picking machine was designed. The structure and working principle of the whole machine were described and the vibration parameters of the upper and lower canopy of camellia fruit were also researched.

(1) Through the analysis of the factors of camellia fruit abscission, it is concluded that frequency, amplitude and working time are the main factors affecting the magnitude of inertia force.

(2) Through preliminary research and coupling simulation, the horizontal range of each factor is determined: the operation time is 5 s, 10 s, 15 s, the frequency is 3 Hz, 5 Hz, 7 Hz and the amplitude is 50 mm, 60 mm, 70 mm.

(3) The results of the orthogonal test were analyzed using the comprehensive scoring method, and the best combination of working parameters for picking camellia fruits in the upper canopy was 15 s of working time, 70 mm of amplitude and 5 Hz of frequency, which corresponded to a leakage rate of 8.21% of camellia fruits and 9.12% of bud damage. The best combination of working parameters for lower canopy picking is 15 s, 50 mm amplitude and 7 Hz frequency, which corresponds to 6.84% leakage rate and 6.92% bud damage rate. The field test results show that the picking machine can meet the picking requirements of the camellia fruit.

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