OPTIMIZATION AND EXPERIMENT ON MECHANICAL VIBRATION HARVESTING PROCESS PARAMETERS OF MULBERRY
/
桑葚机械振动收获参数优化与试验研究

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ABSTRACT
The mechanized harvesting of mulberry is important for its production. In the process of harvesting, it is considered not only the mechanical damage of mulberry fruit but also its harvesting efficiency. It is very important to improve the vibration harvesting efficiency of mulberry. In this study, modal analysis of mulberry trees and harmonic response analysis of branches were carried out to determine the harvesting frequency of the branch's vibration and other parameters. The effects of excitation frequency and vibration position on the triaxial acceleration of the mulberry branch at different positions were analyzed by vibration test. Then the triaxial acceleration of branches at different positions was analyzed. The conditions of the mulberry fruit shedding were obtained through theoretical analysis. Through the 20-order modal analysis of mulberry, it is concluded that a better vibration effect can be achieved when the vibration frequency is controlled at 4-16 Hz. According to the harmonic response analysis, the best excitation frequencies are 5-6 Hz, 10-13 Hz, and 14-16 Hz. The harmonic response analysis of fruit branches was carried out, and the stress of fruit stalks at 5 Hz, 10 Hz, and 15 Hz were analyzed. The result shows that the maximum stress is 2.9252×107 Pa, the excitation position is the first-order branch, and the excitation frequency is 15 Hz. The frequencies obtained from modal analysis and harmonious response analysis were used to conduct experiments. When the excitation frequency was 15 Hz, the triaxial accelerations a_X, a_Y, and a_Z were 2.12 g, 4.16 g, and 3.99 g, respectively, which were more conducive to the shedding of mulberry fruits.

摘要
桑树机械化采收是桑树生产的重要环节。在采收过程中，既要考虑桑树果实的机械损伤，又要考虑桑树果实的采收效率。提高桑树振动采收效率具有十分重要的意义。本研究通过对桑树进行模态分析和对树枝进行谐波响应分析，确定树枝振动的收获频率等参数。通过振动试验，分析了激励频率和振动位置对桑树枝条不同位置三轴加速度的影响。然后对不同位置支路的三轴加速度进行分析。通过理论分析，得出了桑树果实脱落的条件。通过对桑树的 20 阶模态分析，得出当振动频率控制在 4-16hz 时，可以获得较好的振动效果。根据谐波响应分析，最佳激励频率为 5-6Hz、10-13Hz 和 14-16Hz。对果枝进行谐波响应分析，对果柄在 5Hz、10Hz 和 15Hz 下的应力进行分析。结果表明:最大应力为 2.9252x107Pa，激励位置为一阶枝干，激励频率为 15Hz。利用模态分析和协调响应分析得到的频率进行试验。当激励频率为 15Hz 时，三轴加速度 a_X 为 2.12g，a_Y 为 4.16g，a_Z 为 3.99g。更有利于桑树果实的脱落。

INTRODUCTION
Mulberry trees can adapt to various complex and harsh environments, which plays an important role in improving the environment of sandstorm areas. It is known as the most suitable "factory" for sustainable development (*Gulab et al., 2020*). The products of mulberry trees such as mulberry leaves and mulberries are applied in food, pharmaceutical, cosmetics, and various industries. Mulberries are the fruits of mulberry trees, which have rich nutrition and physiological health functions. It is one of the first agricultural products with both food and medicine approved (*Zheng et al., 2016; Xue et al., 2013; Zeng et al., 2019; Xu et al., 2017*). With the planting area of mulberry increased, the mulberry planting area of China reached 796,700 hectares in 2021. The problem of mulberry harvest becomes very important. Therefore, the mechanization of mulberry fresh fruit production becomes very important.

Fruit harvesting is the most critical part of the fruit production process. It is a very seasonal and labor-intensive work. Labor forces account for 30-45% of the fruit production (*Du et al., 2011*). At present, compared with other crops, the mechanization of mulberry fruit harvesting progress is slow. In the process of mulberry harvesting, too low harvest efficiency will cause the large number of fruit to decay, then cause serious economic losses. Therefore, the factors affecting mechanical harvesting efficiency play an important role in the mulberry harvest, which include vibration frequency, amplitude, and excitation position.

Many studies have been done on cherry harvesting, which includes the analysis of energy transfer efficiency with different vibration frequencies. *Liu et al. (2018)* improved the efficiency of mechanical apple harvesting by designing a suitable harvesting mode. They found that a higher harvest rate could be achieved when the change rate of vibration frequency was 8 Hz/s. *Peng et al. (2017)* studied the harvest process of winter jujube by applying the FEM to analyze its dynamic response under vibration excitation at different frequencies. They found out the relationship between acceleration and frequency. *Sergio et al. (2020)* conducted experiments on 22 secondary branches of Valencia orange. They studied the effects of fruit and leaves on the dynamic response of the secondary branches. *Wang et al. (2019)* studied the vibration harvesting efficiency of litchi and concluded that 90% of fruits were defruiting at different speed.

Fu et al. (2019) designed a vibrating screen with adjustable vibration amplitude for harvesting apples. The results show that the vibration amplitude at 30 mm was enough to make fruits fall off and obtain high quality fruits. *Yang et al. (2019)* studied the influence of vibration time, vibration frequency, and vibration excitation point amplitude on apricot tree vibration acceleration and dynamic response in the apricot shedding process. *San et al. (2018)* studied the effect of vibration mode and frequency on the vibration harvesting response of apricot trees. They obtained the acceleration vibration response curves of different positions through vibration transmission from the clamping position.

Ding et al. (2017) studied the dropping characteristics of mulberry fruit, analyzed the main factors affecting the inertia force in the process of vibration harvesting, and obtained the vibration parameters of the vibration harvesting device when the mulberry fell off. *Sun et al. (2023)* proposed a branch stalk fruit of apple as a base system. They investigated the vibration mechanism and separation deformation law of apple tree branches through dynamic tests and simulation.

Alberto et al. (2019) evaluated an innovative system for mulberry fruit harvesting, which increases per capita hourly productivity by three times, but requires at least four workers. *Zhou et al. (2022)* designed a new vibrator for fruit-picking machines with adjustable amplitude. Moreover, the kinematic and dynamic models were set up through theoretical analysis and simulation.

Wang et al. (2023) designed the vibration clamping head of a harvesting machine and conducted vibration shedding tests on mulberry branches at different locations. In conclusion, the research on vibration parameters and dynamic response of various fruit trees is not very perfect, which is difficult to apply to mechanical design and actual production. Moreover, the study on the vibration of mulberry fruit trees is less.

In this study, a mulberry tree model was established to determine the harvesting frequency and other parameters of branch vibration. The effects of excitation frequency and vibration position on the triaxial acceleration of the mulberry tree branch at different positions were analyzed by experiment. Through the comparison of different locations, excitation frequencies, and monitoring points, the influence on mulberry branch acceleration was obtained. Then the influence on mulberry harvest efficiency was analyzed.

MATERIALS AND METHODS

Properties test of mulberry branch

The properties of mulberry branches, including their density and elastic modulus, are the necessary parameters for simulation. Therefore, the bending method was applied to measure the elastic modulus of mulberry branches. The drainage method was applied to measure the density of mulberry branches, which provided the basis for the material properties of the mulberry model. The bending elastic modulus of the mulberry branch was measured based on the three-point bending method. Five periods of mulberry branches were selected. The TMS-Pro professional food property machine was applied for the three-point bending test. The distance between two points is set at 80 mm. To measure the displacement situation of middle position, two different displacement points of each branch were chosen. Then the bending elastic modulus of the mulberry branches was calculated. The determination of bending elastic modulus is shown in Fig. 1.

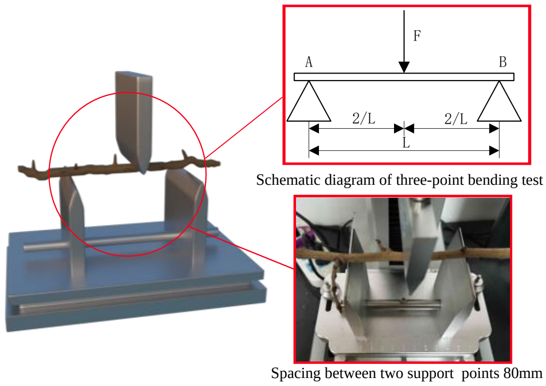


Fig. 1 – Measurement of bending elastic modulus of mulberry branches

The equation for calculating the bending elastic modulus of mulberry branches is shown in Eqs. (1), (2) and (3) (*Feng et al., 2020*).

$$W = \frac{FL^3}{48EI} \tag{1}$$

where: W is the deformation of the mulberry branch, mm; F is the external force applied, N; L is the distance between two support points, mm; E is the bending elastic modulus of mulberry branch MPa; I is the moment of inertia of mulberry branch section, mm^4.

$$I = \frac{\pi d^4}{64} \tag{2}$$

where: d is the cross-section diameter of the mulberry branch, mm.

$$E = \frac{4FL^3}{3W\pi d^4} \tag{3}$$

The three-point bending test was carried out on five different diameters of mulberry branches. Two different dislocations were selected for each branch to measure the elastic modulus. The result is shown in Table 1. It can be drawn that the average bending elastic modulus of mulberry branches is 1981.40 MPa. The maximum flexural elastic modulus is 2189.19 MPa, and the minimum flexural elastic modulus is 1575.87 MPa. The mulberry branches were divided into five sections, then their density values were measured respectively. The average value was taken as the final result of the experiment. Then the branches were put into a measuring cup with a certain scale to calculate the density value of the mulberry tree. The average density of mulberry branches was 804.38 kg/m^3. The test results are shown in Table 2.

Table 1

Bending elastic modulus of mulberry branches

Number	Diameter [mm]	Displacement 1: flexural modulus of elasticity [MPa]	Displacement 2: flexural modulus of elasticity [MPa]	Average value [MPa]
1	3.75	2117.48	2086.03	2101.76
2	3.59	2000.35	1993.29	1996.82
3	4.9	2091.73	2031.88	2061.80
4	4.83	2118.28	2189.19	2153.73
5	6.52	1609.95	1575.87	1592.91
Average value				1981.40

Table 2

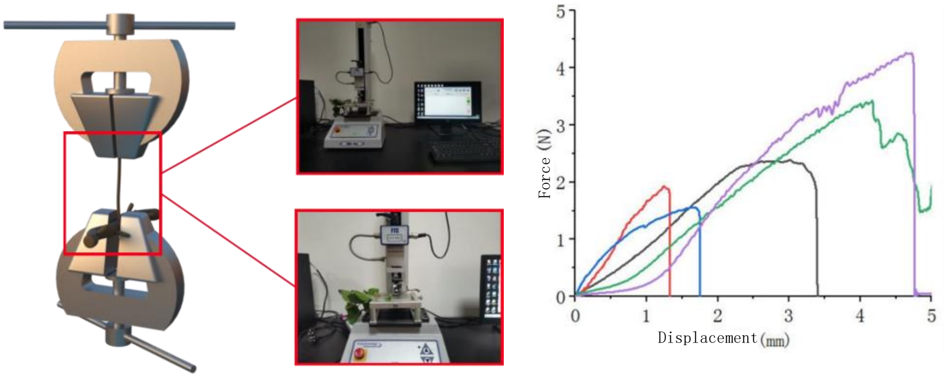
Determination of fresh mulberry fruit density

Number	1	2	3	4	5	Mean value
Mulberry fruit density [kg/m^3]	870.00	596.25	958.72	869.44	727.50	804.38

Fruit separation conditions test

Connecting force between the stalk and fruit

The connection of the fruit with the stalk was measured by the TMS-PRO food physical property analyzer. Shensang's No. 1 mulberry variety was selected as the test material. Firstly, the pulp of mulberry fruit was removed, and the branches connected with the stalk and the fruit were respectively fixed on the base and held on the upper clamp head. Then the stalk was stretched. The connecting relay was measured at the stalk and branch. The connection of the fruit stalk is shown in Fig.2.



Measurement of the connecting force of fruit stalk Force displacement curve

Fig. 2 – Determination of connection of fruit stalk

The fruits were selected for the test, and then the results for the stem connection of mature fruits were obtained, as shown in Table 3. The maximum stem connection of mature fruits is 1.529 N, and the average stem connection of mature fruits is 1.238 N. The immature fruits were selected for the determination of stem connection, as shown in Table 4. The maximum stem connection of immature fruits is 4.715 N, and the average of immature fruits is 3.677 N.

Table 3

Connecting force of fruit stalk of mature fruit

Number	1	2	3	4	5	6	7	8	9	10	Mean value
Fruit stalk connecting force [N]	1.529	1.386	0.925	1.541	1.766	1.030	1.207	1.086	0.965	0.943	1.238

Table 4

Connecting force of immature fruit stalk

Number	1	2	3	4	5	6	7	8	9	10	Mean value
Fruit stalk connecting force [N]	3.407	4.241	4.715	4.256	3.872	4.098	2.875	3.375	2.180	3.749	3.677

Principle of fruit shedding

The stalk connection of mulberry fruits at different growth stages is significantly different. The stalk connection decreases gradually with fruit ripening. The excitation force is applied to the branches of the mulberry tree through the excitation device. The excitation force will be transferred to the mulberry fruit through the branches in the process of vibration. The acceleration generated by the mulberry fruit and the fruit's gravity has an inertial effect, so it will lead to the falling off of the mulberry fruit (*San et al., 2018*).

The spatial stress analysis of mulberry fruits was carried out to analyze the shedding conditions of mulberry fruits. Fig. 3 shows the stress analysis diagram of mulberry fruits. When the combined force of the inertia force along the stem direction (F_n) and the component force of the gravity of the mulberry fruit along the stem direction (F_g) is greater than that of the mature fruit (F_L), mature mulberry fruit falls off. Similarly, F_n and F_g less than immature mulberry fruit peduncle relay (F_W), immature mulberry fruit does not fall off.

$$F_W \geq F_n + F_g \geq F_L \tag{4}$$

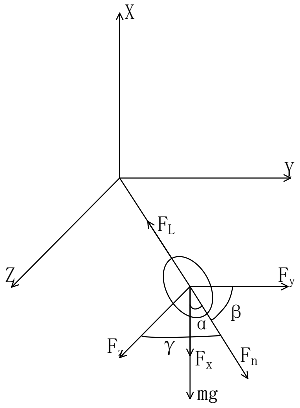


Fig. 3 – Stress analysis of mulberry

where: F_x is the inertia force of Mulberry fruit along the X axis, N; F_y is the inertia force of mulberry fruit along the Y-axis direction, N; F_z is the inertia force of mulberry fruit along the Z axis, N; F_n is the inertia force of mulberry fruit along the X-axis direction, N; F_g is the force of the gravity of mulberry fruit along the stem direction; F_L is the stalk connecting relay of mature mulberry fruit; F_W is connected to the stalk of mature fruit.

The inertia force generated by the acceleration in the X, Y, and Z directions of mulberry fruit caused by vibration is F_x, F_y, and F_z; the acceleration in the three directions is a_X, a_Y, and a_Z respectively; the combined force of the three directions along the stalk direction is F_n.

$$F_X = ma_X$$
$$F_Y = ma_Y$$
$$F_Z = ma_Z \tag{5}$$

$$F_n = F_X \cos\alpha + F_Y \cos\beta + F_Z \gamma \tag{6}$$

where: α is the included angle between the fruit stalk and X-axis; β is the angle between the fruit stalk and Y-axis; γ is the angle between the stalk and Z-axis.

In the vibration harvesting process of mulberry fruit, fruit shedding depends mainly on the inertia force F_n along the stem direction, and the component force of fruit gravity along the stem direction can be ignored. Therefore, the shedding of mature fruits and the non-shedding of immature fruits must ensure that F_n is greater than F_L and less than F_W.

$$F_L \leq ma_X \cos\alpha + ma_Y \cos\beta + ma_Z \cos\gamma \leq F_W \tag{7}$$

Simulation setup procedure

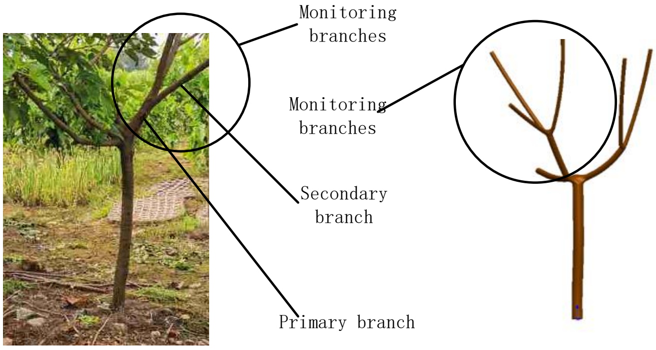
It is established as a three-dimensional model of mulberry according to the measured diameter of mulberry branches. The diameter of the trunk is 80±3 mm, the diameter of the first branch is 45±2 mm, and the diameter of the second branch is 30±2 mm. The selection of mulberry plants is shown in Fig. 4(a). The trunk, primary, and secondary branches of the selected mulberry plants are close to the average diameter measured, and then the height of each branch is appropriate. The material characteristics of mulberry are shown in Table 5. The mulberry model was simplified and established as a secondary branch. The established mulberry tree model is shown in Fig. 4(b).

Table 5

Mulberry parameters

Trunk [mm]	Primary branch [mm]	Secondary branch [mm]	Density [kg/m^3]	Flexural modulus of elasticity [MPa]	Poisson's ratio
80±3	45±2	30±2	804.38	1981.40	0.3

The established model was imported into ANSYS 12.0 software for grid division. To ensure calculation accuracy and avoid excessive computation, the grid size was set to 0.01 m, the number of grids was 19629, and the number of nodes was 32901. Constraints were added to the mulberry tree model, and the bottom and ground of the mulberry trunk were regarded as fixed constraints, so fixed constraints were added to the bottom of the trunk.



(a) Mulberry material object *(b) Mulberry model*

Fig. 4 – Mulberry model and real object

Vibration test of mulberry branches

The mulberry plant of Shenyang No. 1 was selected as experimental material. The main trunk, primary branch (the primary branch is the branch branching upward from the main trunk), and the secondary branch (the second branch is the branch branching from the primary branch) were analyzed respectively.

The instruments and equipment include that TCH adjustable electric reciprocating saw modified vibrator with adjustable frequency, maximum reciprocating frequency is 46.7 Hz, reciprocating stroke is 15 mm, saw blade chuck is applied as vibration head, which is fixed to vibrate fruit trees. The six-axis acceleration sensor can measure the acceleration in X, Y, and Z directions, which is shown in Fig. 5. The vibration frequency, location of the excitation point, and different positions of the three branches were selected as test factors. The branch acceleration in X, Y, and Z directions was selected as test indexes. According to the results, the excitation frequencies of 5, 10, and 15 Hz were selected. The starting end of the first-order branch and the beginning end of the second-order branch were selected as the locations of excitation points. The location of excitation points is shown in Fig. 6. The sensors were placed on the secondary branch, which is shown in Fig. 7. The X-axis is perpendicular to the ground direction upward, the Y-axis is parallel to the ground directly to the direction of branch growth, and the Z-axis is perpendicular to the branch direction. The experimental design is shown in Table 6.

(a) Acceleration sensor *(b) Sensor installation method*

Fig. 5 – BWT61CL six-axis Bluetooth acceleration sensor

(a)Beginning of primary branch *(b) beginning of secondary branch*

Fig. 6 – Location of excitation point

(a)Sensor leveling *(b) sensor layout*

Fig. 7 – Placement mode of the acceleration sensor

Table 6

Experimental design

A: Excitation position	B:(monitoring position) from the starting point of secondary branch[mm]	C: Excitation frequency [Hz]
Primary branch	200, 400, 600	5, 10, 15
Secondary branch	200, 400, 600	5, 10, 15

RESULTS

Modal analysis for vibration

Because the most influential modes are the first several modes, in which the frequency is in the middle and low period, therefore, the first 20 modes of the mulberry model are selected for analysis. The natural frequencies of the 20 modes are obtained. The natural frequencies of mode 20 are shown in Table 7.

Table 7

Natural frequencies of 20th order modes

Order	Natural frequency [Hz]	Order	Natural frequency [Hz]
1	4.1188	11	14.921
2	4.188	12	16.951
3	6.5182	13	20.945
4	7.2701	14	21.603
5	9.7037	15	32.192
6	11.303	16	32.785
7	11.504	17	40.019
8	11.685	18	40.471
9	11.935	19	58.876
10	12.19	20	62.999

From the 14th order, the natural frequency changes significantly. So, the first 14 modal formations were analyzed. The modal response analysis of the mulberry tree is shown in Fig. 8.

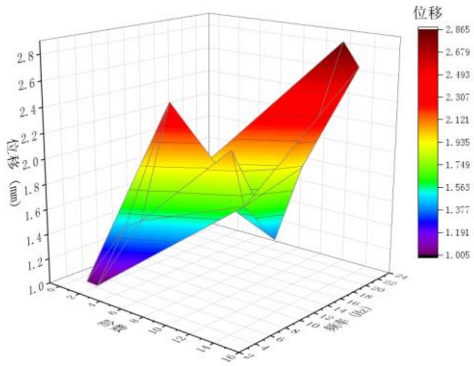


Fig. 8 – Modal response analysis of mulberry

According to the results in Fig. 8, the natural frequency of mulberry at the first order is 4.118 Hz and the deformation is 1.0153 m. The deformation of the mulberry tree was the largest at the 5th, 9th, and 13th steps, which were 2.4277 m, 2.0925 m, and 2.8614 m, respectively. The deformation of mulberry trees at the 6th, 8th, and 12th steps was 1.8555 mm, 1.9471 mm, and 1.9230 mm, respectively. The modal cloud diagram of the mulberry tree is shown in Fig. 9.

With the increase in frequency, the deformation of the tree body increases gradually. According to the typical modal shapes, the trunk and branches wobble slightly in mode 1. The second branch oscillates up and down in the third mode. The first and second branches oscillate up and down in the fifth mode. Most of the secondary branches oscillate from side to side in mode 7. The secondary branch oscillates greatly in mode 9. The main trunk and the first and second branches of the tree oscillate from side to side in mode 11. So, the vibration harvesting frequency of mulberry is controlled within the range of 4-16 Hz.

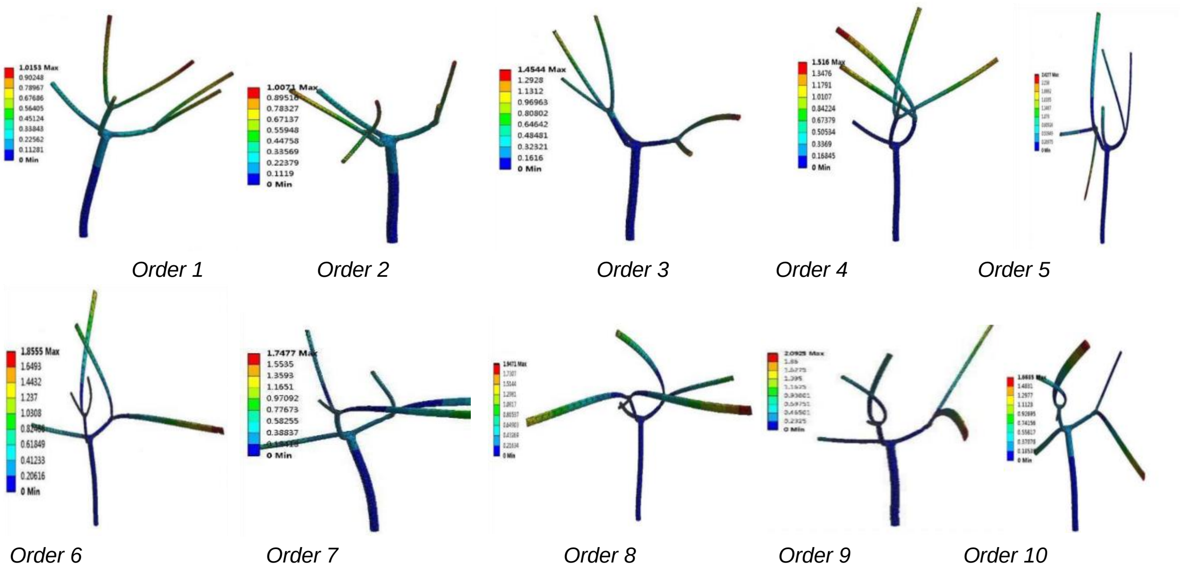


Fig. 9 – Cloud diagram of mulberry modal analysis

Harmonic response analysis

The dynamic response of the mulberry tree under sinusoidal excitation was determined by analyzing the harmonic response of the mulberry tree. If the mulberry fruit is connected to monitoring point 1, the elastic modulus of the fruit stalk can be approximately considered as 80% of the elastic modulus of the branch (Luo et al., 2016). The mulberry branch model is shown in Fig. 10.

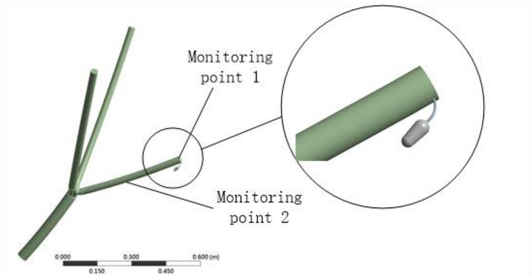
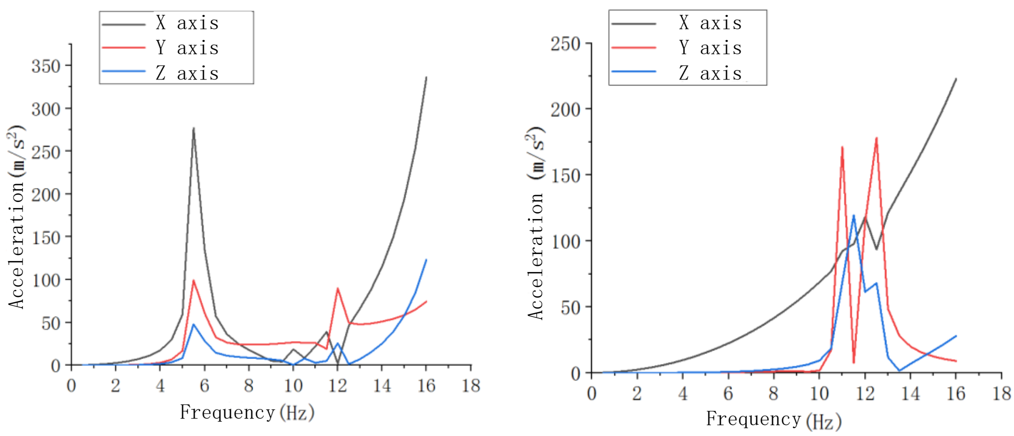


Fig. 10 – Stem model with fruit branch

The excitation point was set at the tail end of the first branch, and the displacement load was set at 15 mm. The frequency range is from 0 to 16 Hz. By analysis, the acceleration curves of the monitoring points can be obtained.

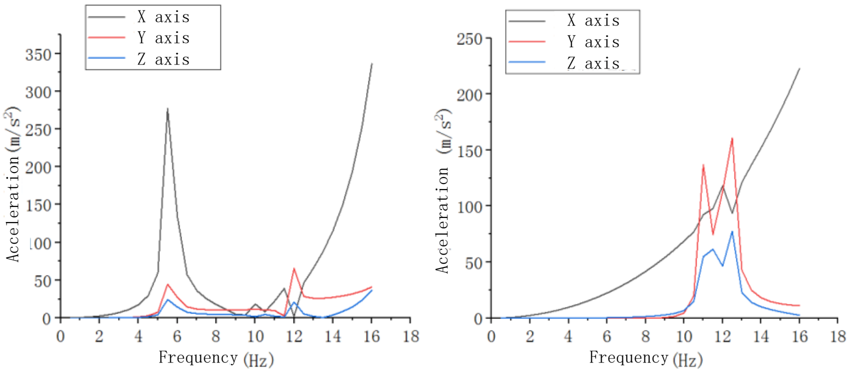
The acceleration curve of monitoring point 1 is shown as Fig. 11. The acceleration curve of monitoring point 2 is shown as Fig. 12.



(a)Loading position primary branch start; (b) Loading position secondary branch start

Fig. 11 – Acceleration change curve of monitoring point 1

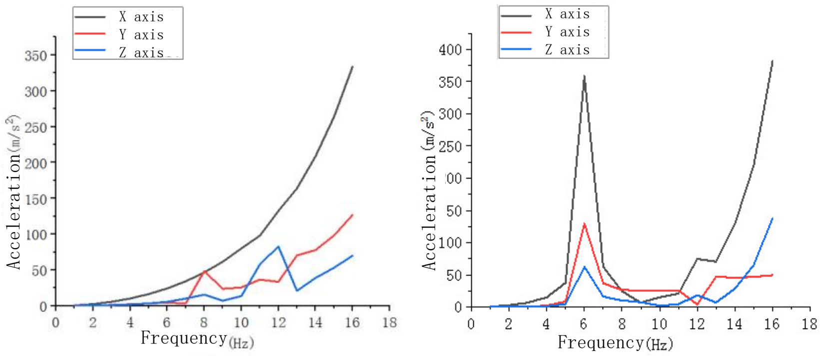
It is defined that the X-axis direction is consistent with the loading direction, Y-axis is vertical to the ground, and the z-axis direction is vertical to the loading direction and horizontal to the ground. When the test begins at the primary branch, the three-axis acceleration of the monitoring point in the set frequency interval has a typical peak acceleration at 5.5 Hz, the X-axis acceleration has a typical peak acceleration at 10 Hz and 11.5 Hz, and the Y-axis acceleration has a typical peak acceleration at 12 Hz. The Z-axis acceleration has typical velocity peak values at 10.5 Hz and 12 Hz. When the excitation point is the beginning of the secondary branch, the X-axis acceleration has a typical velocity peak at 12 Hz, the Y-axis acceleration has a typical velocity peak at 11 Hz and 12.5 Hz, and the Z-axis acceleration has a typical velocity peak at 11.5 Hz and 12.5 Hz. Moreover, the triaxial acceleration speed increases with the increase of frequency to 16 Hz after the peak.



(a)Loading position primary branch start; (b) Loading position secondary branch start

Fig. 12 – Acceleration change curve of monitoring point 2

The acceleration curve of the mulberry fruit is shown in Fig.13. It can be seen from Fig. 13 (a) that when the excitation frequency is 8 Hz, the Y-axis acceleration has a typical peak acceleration. When the excitation frequency is 12 Hz, the z-axis acceleration has a typical peak value. The X-axis acceleration increases as the frequency increases. It can be seen from Figure 13(b) that when the excitation frequency is 6 Hz, the three-axis accelerations all have typical peak accelerations. The triaxial acceleration is at the peak at 12-13 Hz, but it is not obvious. When the vibration frequency is more than 13 Hz, the triaxial acceleration increases with the increase of vibration frequency.

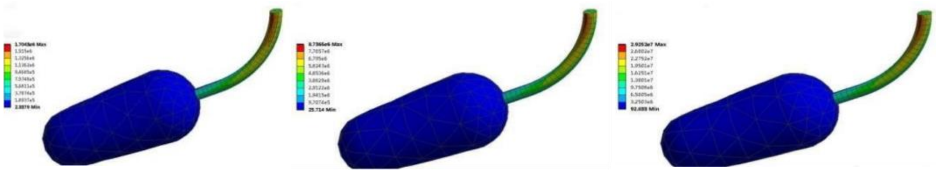


(a)Loading position primary branch start; (b) Loading position secondary branch start

Fig. 13 – Acceleration curve of mulberry fruit

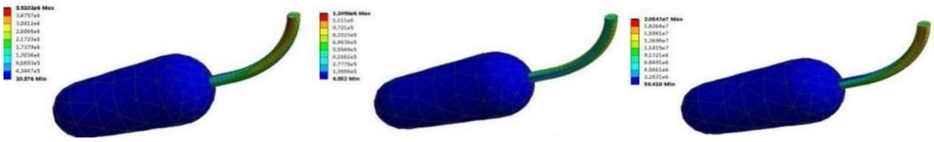
The response analysis shows that the peak point and the high point of acceleration mostly exist in the period of 5-6 Hz, 10-13 Hz, and 14-16 Hz. Therefore, the vibration test adopts 5 Hz, 10 Hz, and 15 Hz to experiment.

The initial end of the primary branch and the secondary branch were stimulated respectively to analyze the stress of the fruit stalk when the excitation frequency was 5 Hz, 10 Hz, and 15 Hz. The stress cloud of the fruit stalk of the excited primary branch is shown in Fig. 14. The stress cloud of the fruit stalk of the excited secondary branch is shown in Fig. 15.



(a) 5Hz (b) 10Hz (c) 15Hz

Fig. 14 – Stress nephogram of fruit stalk of primary branch excited by vibration



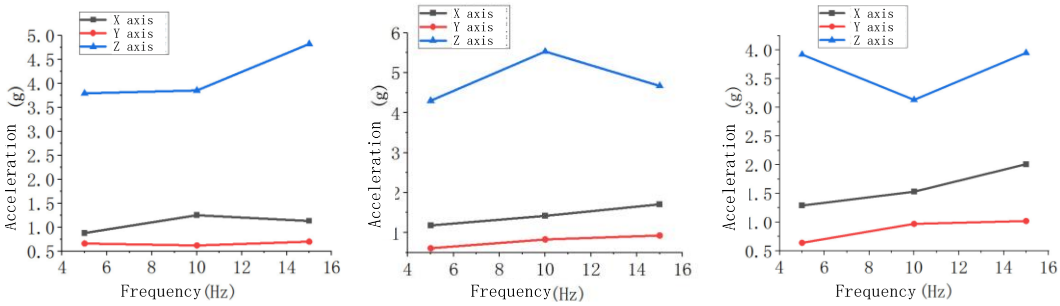
(a) 5Hz (b) 10Hz (c) 15Hz

Fig. 15 – Stress nephogram of secondary branch fruit stalk excited by vibration

The stress concentration area at the fruit stalk is the connection area between the fruit stalk and the branches. When the mulberry fruit falls off with vibration, the connection area between the fruit stalk and the branches is broken. The fruit shedding stress is 394267.52 Pa according to the ratio of cloud pulling force to fruit stalk cross-sectional area. When the excitation frequency is 5, 10, and 15 Hz, the maximum stress is 1.7043×10^{6}, 8.7365×10^{6}, and 2.9252×10^{7} Pa. When the excitation frequency is 5, 10, and 15 Hz, the maximum stress is 3.9102×10^{6}, 1.2796×10^{6}, and 2.0547×10^{7} Pa respectively. The result shows that the maximum stress is 2.9252×10^{7} Pa. The result shows that when the excitation frequency is 15 Hz, the fruit is easier to fall off and the vibration harvesting efficiency can be improved.

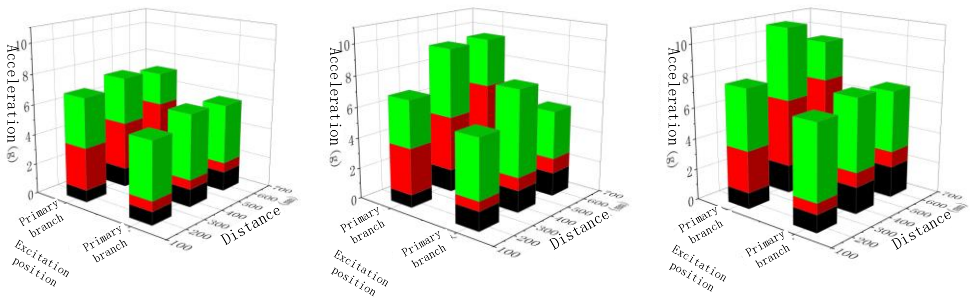
Vibration experiment results and analysis

In the process of vibration harvesting of mulberry fruit, different excitation frequencies and locations have an impact on fruit shedding. Moreover, the triaxial branching acceleration will be different in condition of different excitation frequencies and locations. The triaxial acceleration at different excitation frequencies and different excitation positions was analyzed. The influence of different excitation positions on triaxial acceleration is shown in Fig. 16. The influence of different excitation frequencies on the triaxial acceleration is shown in Fig. 17.



(a) 200mm *(b) 400mm* *(c) 600mm*

Fig. 16 – Triaxial acceleration of exciting primary branch



(a) 5Hz *(b) 10Hz* *(c) 15Hz*

Fig. 17 – Shows the triaxial acceleration at different excitation positions

The significance analysis shows that the excitation frequency has a significant effect on the branch acceleration of the X-axis ($P<0.01$), the branch acceleration of the Y-axis ($P=0.0035<0.01$), and has no significant effect on the branch acceleration of the Z-axis ($P=0.056>0.05$). The vibration position had no significant effect on the branch acceleration of the X-axis ($P=0.054$), had a very significant effect on the branch acceleration of the Y-axis ($P<0.01$), and had a very significant effect on the branch acceleration of the Z axis ($P=0.009<0.01$). The monitoring position had a significant influence on the branch acceleration of the X-axis ($P<0.01$), Y-axis ($P<0.01$), and Z-axis ($P=0.065>0.05$).

When the excitation frequency is 15 Hz and the position is 600 mm away from the starting point of the secondary branch, the acceleration on the X-axis is the largest, which is 2.43 g. When the excitation frequency is 15 Hz, the maximum Y-axis acceleration is 4.41 g at the position 600 mm away from the starting point of secondary branching. When the excitation frequency is 10 Hz, the maximum z-axis acceleration is 5.53 g at 400 mm from the starting point of the secondary branch.

A hybrid optimization of three indexes was carried out for three-axis acceleration. Optimization conditions are as follows:

$$\begin{cases} max a_X\ (\mathrm{A},\ \mathrm{B},\ \mathrm{C}) & \mathrm{A}:\ \text{Primary branches, secondary branch} \\ max a_Y\ (\mathrm{A},\ \mathrm{B},\ \mathrm{C}), \text{in}, & 200 \le \mathrm{B} \le 600 \\ max a_Z\ (\mathrm{A},\ \mathrm{B},\ \mathrm{C}) & 5 \le \mathrm{C} \le 15 \end{cases} \quad (8)$$

When the excitation frequency is 15 Hz, the triaxial maximum accelerations a_X, a_Y, and a_Z of the branch are 2.12 g, 4.16 g, and 3.99 g, respectively. Therefore, when the excitation frequency is 15 Hz, it is more conducive to the shedding of mulberry fruits.

CONCLUSIONS

The principle of fruit shedding of mulberry was analyzed. The effects of excitation frequency, vibration position, and detection position on the triaxial branch acceleration of the mulberry branch were studied. The triaxial acceleration of the branch was measured by a six-axis acceleration sensor. By comparing the influence of different excitation positions, vibration frequencies, and detection points on mulberry branch acceleration, the acceleration influence law under different factors in the mulberry mechanized vibration harvesting process was obtained. Through theoretical analysis, it is found that the peak acceleration of the X, Y, and Z axes of mulberry fruit is easier to harvest when the frequency is 5-6 Hz, 10-13 Hz, and 14-16 Hz respectively.

The mean value of stem to trunk connection relay in mature mulberry fruits is 1.238 N, while in immature mulberry fruits it is 3.677 N. Through the modal analysis of mulberry trees, it can be seen that the best vibration effect can be achieved by controlling the vibration frequency within the range of 4-16 Hz. According to the harmonic response analysis, the best excitation frequencies are 5-6 Hz, 10-13 Hz, and 14-16 Hz. The harmonic response analysis of fruit branches was carried out, and the stress of fruit stalks at 5 Hz, 10 Hz, and 15 Hz were analyzed. The maximum stress was 2.9252×10^7 Pa, the excitation position was the first-order branch, the excitation frequency of which was 15 Hz.

When the excitation frequency was 15 Hz, the triaxial accelerations a_X, a_Y, and a_Z of branches were 2.12 g, 4.16 g, and 3.99 g respectively. The position from the starting point of the secondary branches was 488.25 mm. Therefore, when the excitation frequency is 15 Hz, it is more conducive to the shedding of mulberry fruits.

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REFERENCES

[1] Assirelli, A., Stagno, F., Cocchi, A., Sirri, S., Saviane, A., Giovannini, D., & Cappellozza, S. (2019). Innovative system for mulberry fruit harvesting. *Journal of Berry Research*, 9(4), 615-630. https://doi.org/10.3233/JBR-190411

[2] Castro-Garcia, S., Aragon-Rodriguez, F., Arias-Calderón, R., Sola-Guirado, R. R., & Gil-Ribes, J. A. (2020). The contribution of fruit and leaves to the dynamic response of secondary branches of orange trees. *Biosystems Engineering*, 193, 149-156. https://doi.org/10.1016/j.biosystemseng.2020.02.019

[3] Chen, D., Du, X., & Zhang, Q. (2011). Mechanism of vibratory fruit harvest and review of current advance. *Transactions of the Chinese Society of Agricultural Engineering*, 27(8), 195-200. https://doi.org/10.3969/j.issn.1002-6819.2011.08.033.

[4] Ding, H. X., Li, M. T. & Xue, Z. M. (2017). The test device design and vibration of main low order resonance frequency of picking mulberry. *Journal of Agricultural Mechanization Research*, Vol.39, Issue 08: 159-164. https://doi.org/10.3969/j.issn.1003-188X.2017.08.032.

[5] Fu, H., Duan, J., Karkee, M., He, L., Xia, H., Li, J., & Zhang, Q. (2019). Effect of shaking amplitude and capturing height on mechanical harvesting of fresh market apples. *IFAC-PapersOnLine*, 52(30), 306-311. https://doi.org/10.1016/j.ifacol.2019.12.553

[6] Ghosh, A., Gangopadhyay, D., & Chowdhury, T. (2017). Economical and environmental importance of mulberry: a review. *International Journal of Plant and Environment*, 3(2), 51-58. https://doi.org/10.18811/ijpen.v3i02.10437

[7] He, L., Zhou, J., Du, X., Chen, D., Zhang, Q., & Karkee, M. (2013). Energy efficacy analysis of a mechanical shaker in sweet cherry harvesting. *Biosystems Engineering*, 116(4), 309-315. https://doi.org/10.1016/j.biosystemseng.2013.08.013

[8] Liu, M., Wang, F., Xing, H., Ke, W., & Ma, S. (2018). The experimental study on apple vibration harvester in tall-spindle orchard. *IFAC-PapersOnLine*, 51(17), 152-156. https://doi.org/10.1016/j.ifacol.2018.08.079

[9] Peng, J., Xie, H., Feng, Y., Fu, L., Sun, S., & Cui, Y. (2017). Simulation study of vibratory harvesting of Chinese winter jujube (Zizyphus jujuba Mill. cv. Dongzao). *Computers and Electronics in Agriculture*, 143, 57-65. https://doi.org/10.1016/j.compag.2017.09.036

[10] San, Y. L., Yang, H. M., Wang, X. N., Guo, W. S., & Hou, S. L. (2018). Dynamic response analysis of apricot fruit dropping during vibration harvesting. *Trans. Chin. Soc. Agric. Eng*, 34, 68-75. https://doi.org/10.11975/j.issn.1002-6819.2018.18.009

[11] San, Y. L., Yang, H. M., Wang, X. N., Niu, C. H., & Guo, W. S. (2018). Effects of vibration mode and frequency on vibration harvesting of apricot trees. *Journal of Agricultural Engineering*, 34(8), 10-17. https://doi.org/10.11975/j.issn.1002-6819.2018.08.002

[12] Sun, X., Wu, W., Cao, C., Xu, L., Jiang, R., Fang, L., ... & Lu, X. (2023). Research on vibration response characteristics and separation deformation law of fruit-branch system. AIP *Advances*, 13(6). https://doi.org/10.1063/5.0153355

[13] Torregrosa, A., Albert, F., Aleixos, N., Ortiz, C., & Blasco, J. (2014). Analysis of the detachment of citrus fruits by vibration using artificial vision. *Biosystems Engineering*, 119, 1-12. https://doi.org/10.1016/j.biosystemseng.2013.12.010

[14] Wang, C., Li, C J., Lin, W L., & Lin, J L. (2023). Low frequency resonance clamping and fruit picking: A case study of mulberry picking. *Southern Agricultural Machinery* (23),86-87+128. https://doi.org/10.3969/j.issn.1672-3872.2023.23.021

[15] Wang, W., Lu, H., Zhang, S., & Yang, Z. (2019). Damage caused by multiple impacts of litchi fruits during vibration harvesting. *Computers and Electronics in Agriculture*, 162, 732-738. https://doi.org/10.1016/j.compag.2019.04.037

[16] Xu, Y., Zhang, C., Chen Z. H., & Xu, H. (2017). The development of fruit mulberry researching, processing and utilizations. *Food Research and Development*. 38(16), 209-213. https://doi.org/10.3969/j.issn.1005-6521.2017.16.045

[17] Yang, H. M., San, Y. L., Chen, Y. F., Wang, X. N., Niu, C. H., & Hou, S. L. (2019). Influence of different vibration characteristic parameters on vibration response of apricot trees. *Transactions of the CSAE*, 35(2), 10-16. https://doi.org/10.11975/j.issn.1002-6819.2019.02.002

[18] Zheng, D., Li, H., Lin, X., & Zhang, X. (2016). Application prospect of developing mulberry silkworm on soil desertification area of the northwest of Liaoning province. *Journal of Shenyang Normal University (Natural Science Edition)*, 28(4), 268-271. https://doi.org/10.3969/j.issn.2095-5456.2016.04.004

[19] Zhou, J., He, L., Zhang, Q., & Karkee, M. (2014). Effect of excitation position of a handheld shaker on fruit removal efficiency and damage in mechanical harvesting of sweet cherry. *Biosystems engineering*, 125, 36-44. https://doi.org/10.1016/j.biosystemseng.2014.06.016

[20] Zhou, X., & He, Z. (2022). Analysis and simulation of excitation mechanism of variable amplitude vibration type forest fruit picker. *Mechanical design* (10), 105-113. The doi: 10.13841 / j.carol carroll nki JXSJ. 2022.10.015. https://doi.org/10.13841/j.cnki.jxsj.2022.10.015