RESEARCH ON THE RESPONSE MECHANISM OF CLAMPING POINT POSITION TO THE VIBRATION PROPAGATION CHARACTERISTICS OF WOODEN MATERIALS /
夹持点位置对木质材料振动传播特性的响应机理研究

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ABSTRACT
Vibratory harvesting is to dislodge fruits by applying excitation force to fruit trees, so the vibration response characteristics of fruit trees are of great significance for vibratory forest and fruit harvesting machinery to realize efficient harvesting. The effects of different clamping points and vibration frequencies on vibration responsiveness and energy transfer in Broussonetia papyrifera branches are investigated in this study. The results show that the effects of different clamping point positions and vibration frequencies on the branch vibration response are mutual. The ideal distance between the clamping point position and the base of the main branch should be between 48% and 73% of the branch length, and the distance between the clamping point position and the base of the main branch increased with the increase of vibration frequency. This is because, when the clamping point is close to the base of the main branch, a higher excitation frequency increases the energy consumption at the base of the main branch, and the amount of ineffective vibration energy transferred to the base of the main branch also increases. Therefore, when the location of the clamping point is close to the base of the main branch, the suppression of high-frequency vibration at the base of the main branch is stronger than the suppression of low-frequency vibration. When the clamping point is located in the center of the branch, the overall response of the branch to vibration is better.

摘要
振动采收是通过对果树施加激振力使果实脱落，因此果树的振动响应特性对振动林果采收机械实现高效采收具有重要意义。本研究探讨了不同夹持点和振动频率对构树枝条振动响应和能量传递的影响。结果表明，不同夹持点位置和振动频率对枝条振动响应的影响是相互的。理想的夹持点位置与主枝基部之间的距离应为枝条长度的 48% 至 73%，夹持点位置与主枝基部之间的距离随着振动频率的增加而增加。这是因为，当夹持点靠近主枝基部时，较高的激振频率会增加主枝基部的能量消耗，同时传递到主枝基部的无效振动能量也会增加。因此，当夹持点位置靠近主枝基部时，对主枝基部高频振动的抑制作用强于对低频振动的抑制作用。当夹持点位于树枝中心时，树枝对振动的整体响应效果较好。

INTRODUCTION
China is the world's top producer of forest fruits (*Liu et al., 2020*). The majority of forest fruits are being harvested manually, which significantly puts more financial strain on fruit farmers. For example, 50%~70% of the entire cost is attributable to the hand harvest of apricot fruits (*Lin et al., 2016; Wang et al., 2012*). A huge labor force is needed to harvest the forest fruit once it is fully developed. Some forest fruits are not picked as a result of the decline in rural population (*Chen et al., 2019*). As a result, it is one of the best ways to increase the level of automated fruit harvesting (*Pu et al., 2023*).

The three primary categories of vibratory harvesting equipment at the moment are pneumatic, impact, and mechanical, with mechanical vibratory harvesting being the most prevalent (*Yuan et al., 2022; Liu, 2018; Xu et al., 2023*). The clamping device on vibratory harvesting equipment applies vibration to the fruit tree, which causes the fruit to vibrate until it is detached from the tree. The vibration structure, vibration amplitude, vibration frequency and other parameters of vibration harvesting machinery are studied to provide reference for the efficient operation of vibration harvesting machinery (*Fu et al., 2016; Wu et al., 2014; He et al., 2020; Pezzi et al., 2009*). The energy transmission from the clamping point to the fruit is accomplished through the fruit tree vibration, therefore, the study of fruit tree vibration response and energy transmission is crucial.

Fruit trees have a wide range of shapes in their natural growth stage, and dynamic modeling or 3D modeling combined with finite elements can be used to better understand the modal and vibrational response of fruit trees (*Sergio et al., 2020; Peng et al., 2017; Cao et al., 2023*). The research on vibration response and energy transfer under different vibration conditions can provide a better reference for the design and optimization of vibratory harvesting machinery (*Wu et al., 2022; Liu et al., 2018; Wei et al., 2017*). However, little is known about how fruit trees may efficiently use vibration energy under various vibrational conditions (*Du et al., 2012*). This research primarily examines the vibration response and energy flow transfer properties of tree branches using sinusoidal excitation force at various clamping positions and vibration frequencies. This work can serve as a theoretical guide for the later design of the clamping mechanism for vibrating harvesting equipment and the investigation of fruit trees vibration response mechanisms.

MATERIALS AND METHODS

Test materials

The test subject is 3.6 m-tall *Broussonetia papyrifera*, which is seven years old. Its trunk diameter is 39.7 mm, primary branch diameter is 25.4 mm, and secondary branch diameter is 11.7 mm. It mainly consists of two main branches and several subordinate branches (*Niu et al., 2022*). The 2D structure and the placement of the clamping point schematic diagram are shown in Fig. 1.

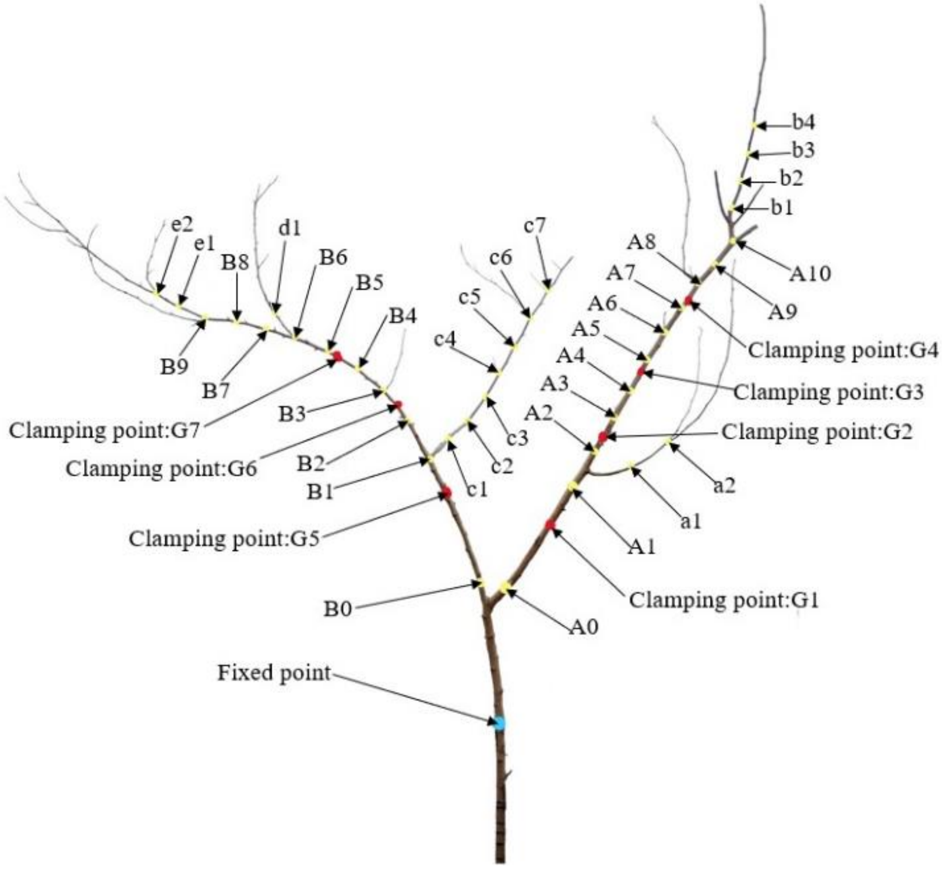

Fig. 1 - Structure of Broussonetia papyrifera

Test methods

Test equipment

Figure 2 shows the test equipment which is a homemade shaking branch type variable frequency and variable amplitude vibration harvesting device, manufactured by the Mechanical Damage and Multiscale Materials Mechanics Laboratory of Anhui Agricultural University. It comprises six-axis acceleration sensors WT61PC-485 (Range: 0~16g. Weight: 24g. Data acquisition frequency: 0~200 Hz), data acquisition system, tape measure, vernier caliper.

The rocking branch type variable frequency and vibration amplitude acquisition mechanism mainly consists of servo motor, reducer, coupling, output shaft, screw rod fixing seat, screw rod, screw rod nut, connecting rod and push rod. The overall structure of the device is a centering crank-slider mechanism. By rotating the screw, the distance between the connecting rod and the output shaft can be adjusted, thus the amplitude can be adjusted.

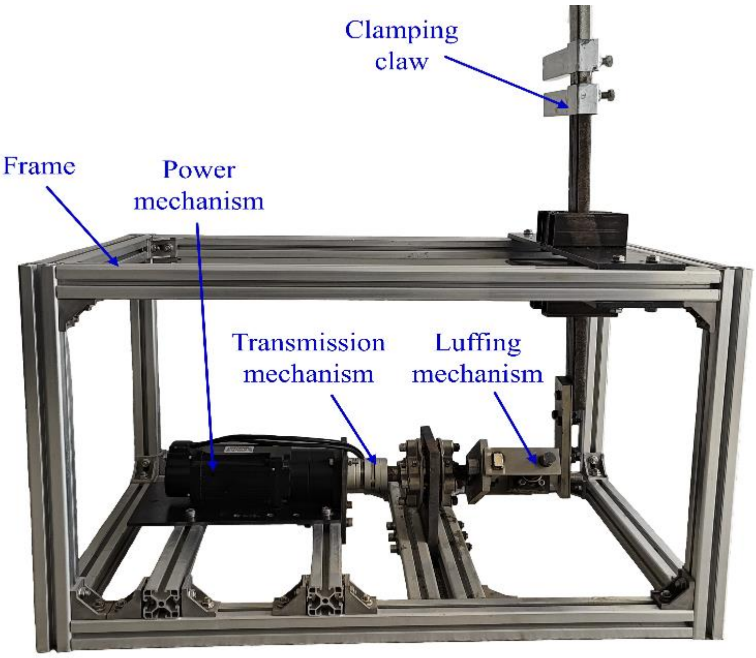

Fig. 2 - Shaking branch vibration harvesting mechanism

Testing planning

Figure 3 shows a picture of the field test of the vibration response characteristics, in which the branch clamping position was 45 cm away from the trunk, which was held in place by a tabletop clamp. Type A branches have a diameter of 21 to 34 centimeters, whereas Type B branches have a diameter of 14 to 24 centimeters. Four grasping points, G1, G2, G3, and G4, are provided on the A branch while three gripping points, G5, G6, and G7, are provided on the B branch, taking into account the manipulator's minimum gripping diameter. The distances between the different clamping points and the trunk are shown in table. 1.

Table 1

Distance between different clamping points and tree trunk

Clamping position	G1	G2	G3	G4	G5	G6	G7
Distance(cm)	45	72	99	126	45	72	99

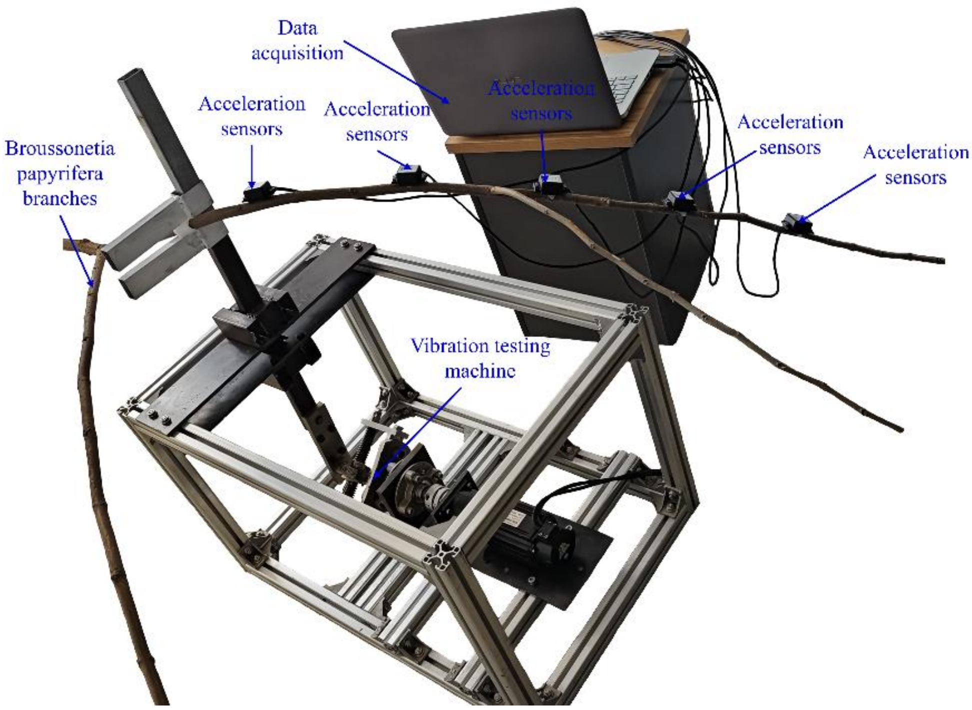

Fig. 3 - Field testing of vibration response characteristics

Monitoring sites A0 and B0 were utilized to measure the vibration response at the branch's base during vibration at a distance of 10 cm from the trunk, as illustrated in Fig. 1. It can show the intensity of the resulting vibration response at the tree trunk. This is an invalid transmission of vibration energy since the vibration of the tree trunk created in this way cannot enable the other principal branches to produce a strong enough vibration response to cause the fruit to fall off. The monitoring places A1 and B1 in Fig. 1 are used to measure the vibration response of the branches and are situated 55 cm from the trunk. In Fig. 1, the Monitoring point A2 and A1 are separated by 15 centimeters, the monitoring point B2 and B1 are separated by 15 centimeters, and the remaining sensors are separated by 10 centimeters.

These sensors are used to track the effective transfer of vibration energy as well as the response of the tree branches to vibration. Considering of the impact of branch diameter on accelerometer stability, all accelerometer attachment sites had branch sizes greater than 10 mm. The branches were clamped at various clamping points and vibrated at various vibration frequencies (2 Hz, 3 Hz, and 4 Hz), with each monitoring point measuring the acceleration of the vibration. Each series of tests was conducted three times and the average of the results was calculated, in order to confirm the accuracy of the results. The movement state of the tree branches could be used to assess the vibration response. Since the vibration was triggered by sinusoidal movement, the acceleration of different points could be integrated to obtain the maximum speed, and formula 1 could be used to calculate the maximum kinetic energy of various monitoring points on the tree branches.

$$E_i=\frac{1}{2}m_i v_i^2=\frac{1}{2}\rho A_i\left(\int a_i\,dt\right)^2 \tag{1}$$

where:

E_i - is the kinetic energy of i monitoring point, (J);

m_i - is the mass of the i monitoring point, (m);

v_i - is the velocity of the i monitoring point, (m/s);

ρ - is the branch density, (kg/m^3);

A_i - is the branch cross sectional area, (m^2);

a_i - is the acceleration of i monitoring point, (m/s^2);

t - indicates the time, (s).

A relative kinetic energy ratio r_{ij} is established to depict kinetic energy changes at monitoring locations i and j along a transmission channel in order to more precisely illustrate the change in response at a specific location in relation to a reference point:

$$r_{ij}=\frac{E_i}{E_j}=\frac{A_i(\int a_i dt)^2}{A_j(\int a_j dt)^2} \tag{2}$$

where:

r_{ij} denotes the proportion of kinetic energy between monitoring points i and j. The cross-sectional areas of i monitoring point and j monitoring point are denoted by A_i (m^2) and A_j (m^2) respectively, whereas i monitoring point and j monitoring point acceleration are denoted by a_i (m/s^2) and a_j (m/s^2) respectively. When calculating the relative kinetic energy ratio on a branch, the value of j in formula 2 is assumed to be 1. The relative kinetic energy ratio can represent the ratio of the effective vibration energy to the ineffective vibration energy when the branch vibrates when j is monitoring point 0 and i is monitoring point at the branch's end.

RESULTS

Influence of clamping points on branch vibration

The effects of vibration on the A-branch and B-branch for various clamping points are depicted in Fig. 4 and Fig. 5 respectively. As illustrated in A2-45 in Fig. 4 (a), A3-72 in Fig. 4 (b), and A4-99 in Fig. 4 (c), with a rise in excitation frequency, the separation between the excitation point and the trunk that generates the optimal excitation response for the A branch grows. This suggests that when the excitation point is close to the base of the A branch, a lower excitation frequency generates a better vibration response. However, at high-frequencies vibration, the branches near the source of excitation generate larger damping forces, preventing effective vibration transmission. The G4 and G7 vibration clamping points have the worst overall effects on the vibration response of branches at the same vibration frequency.

This could be because the clamping point transfers the least amount of energy per unit time to the excitation points G4 and G7, which are the furthest from the branch's base and produce the least vibration in the fruiting branch.

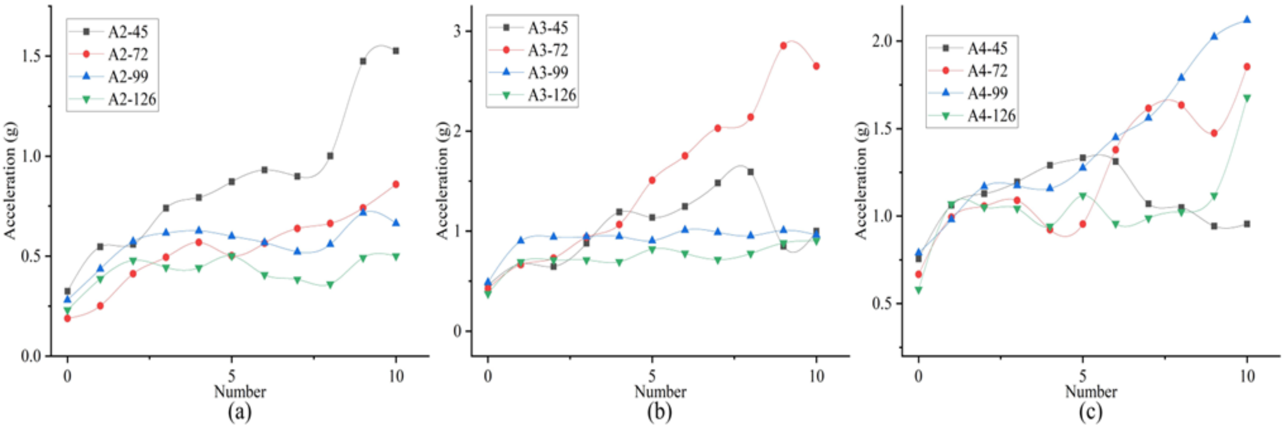

Fig. 4 - Influence of different clamping points on vibration response of A branch
(a): Vibration frequency is 2 Hz; (b): Vibration frequency is 3 Hz; (c): Vibration frequency is 4 Hz.

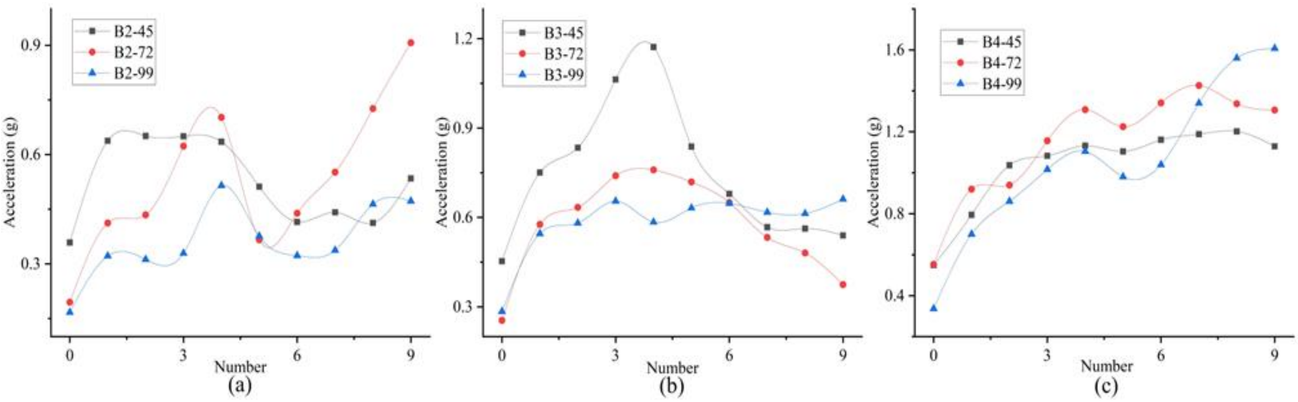

Fig. 5 - Influence of different clamping points on vibration response of B branch
(a): Vibration frequency is 2 Hz; (b): Vibration frequency is 3 Hz; (c): Vibration frequency is 4 Hz.

The relative kinetic energy ratio of each monitoring point on the A branch to the A1 monitoring point at various clamping positions is shown in Fig. 6, and the ratio of each monitoring point on the B branch to the B1 monitoring point at various clamping positions is shown in Fig. 7. The graph in Fig. 6 shows that the relative kinetic energy of A branch is significantly high near its terminal. The result in Fig. 7 shows that the relative kinetic energy of the B branch is quite high at the B4 monitoring point. This is because the branch deflection angle affects how vibrational energy is transferred. The energy transfer is typically hindered by a bigger branch deflection angle, which results in a higher relative kinetic energy ratio.

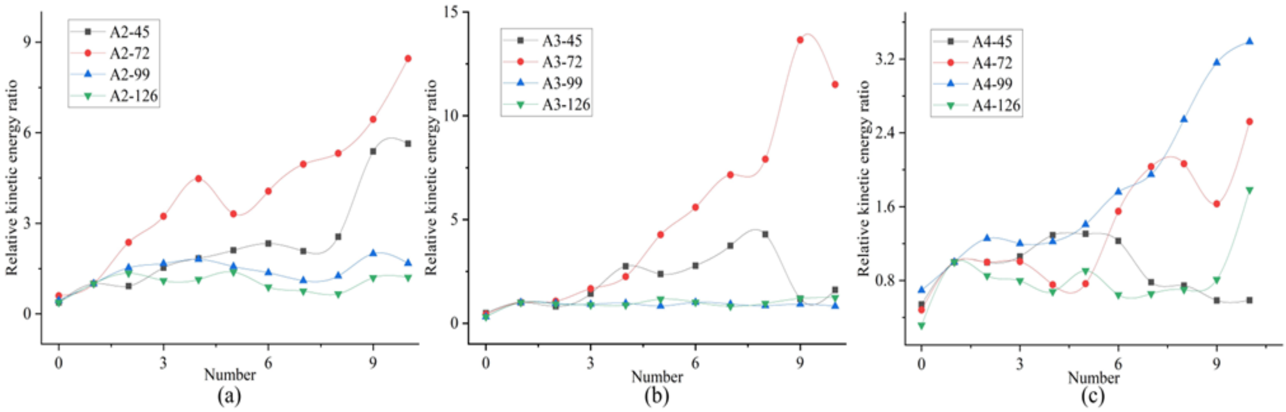

Fig. 6 - Influence of different clamping points on relative kinetic energy ratio of A branch
(a): Vibration frequency is 2 Hz; (b): Vibration frequency is 3 Hz; (c): Vibration frequency is 4 Hz.

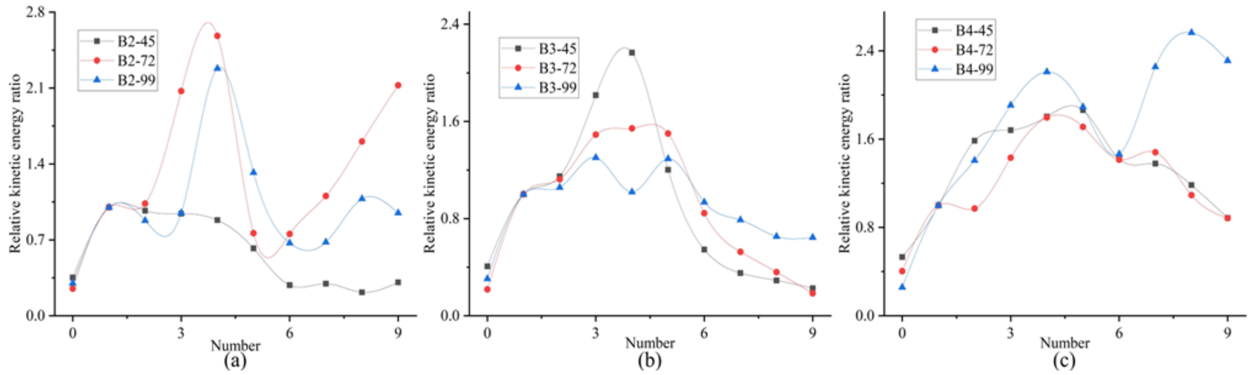

Fig. 7 - Influence of different clamping points on relative kinetic energy ratio of B branch
(a): Vibration frequency is 2 Hz; (b): Vibration frequency is 3 Hz; (c): Vibration frequency is 4 Hz.

Fig. 8 and Fig. 9 show, respectively, the vibrational effects of various vibration clamping points on the *b* branch and *c* branch. The vibration response of the secondary branch is observed to be stronger than that of the primary branch at the same vibration condition, which is favorable for the vibration shedding of fruits. It's possible that the secondary branch requires less energy to produce apparent vibration response because its diameter is substantially less than the primary branch's. Compared to the primary branch, the secondary branch's vibration response is more sensitive to changes in the clamping point's position. It demonstrates the choice of the clamping point position can significantly impact the effectiveness of fruit vibration harvesting.

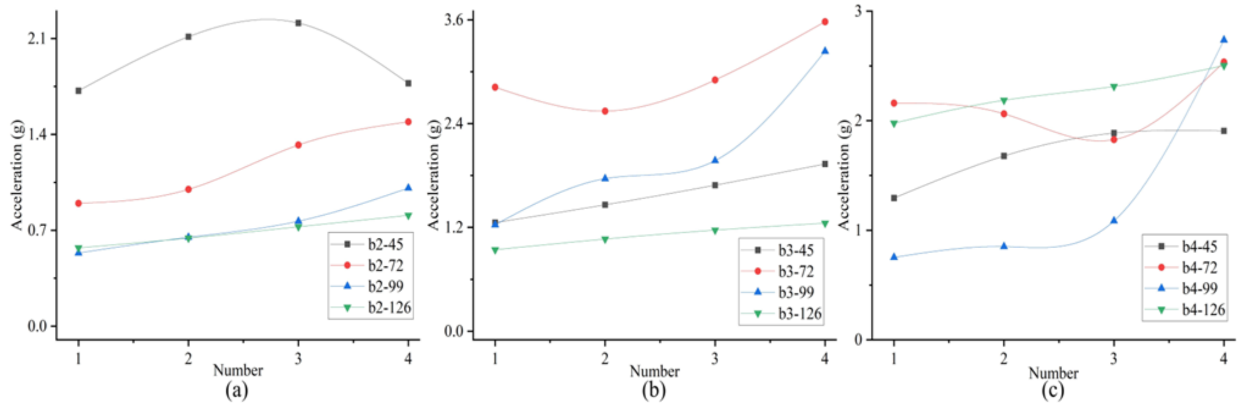

Fig. 8 - Influence of different clamping points on vibration response of b branch
(a): Vibration frequency is 2 Hz; (b): Vibration frequency is 3 Hz; (c): Vibration frequency is 4 Hz.

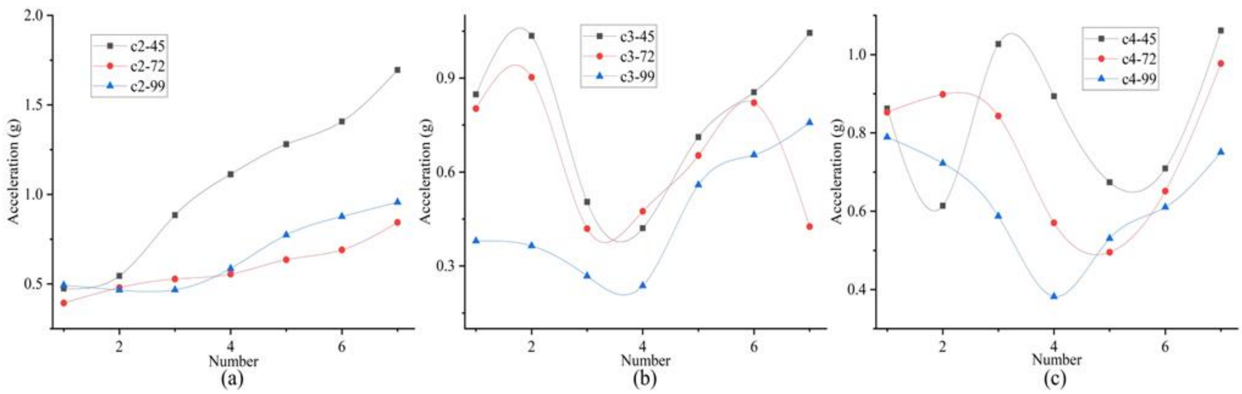

Fig. 9 - Influence of different clamping points on vibration response of c branch
(a): Vibration frequency is 2 Hz; (b): Vibration frequency is 3 Hz; (c): Vibration frequency is 4 Hz.

Influence of vibration frequency on branch vibration

Fig. 10 and Fig. 11 show, respectively the vibrational impacts of various vibration frequencies on the A branch and the B branch. It has been discovered that tree branches respond better to high frequency vibration than low frequency vibration. Under high-frequency vibration, the manipulator is able to transfer more kinetic energy to the branch clamping point with in a certain period of time, which results in higher energy density and better vibration responsiveness of the branch.

As illustrated by monitoring points 4 and 5 in Fig. 11 (a), under various vibration frequencies, the acceleration change amplitudes of the same monitoring points of branch A and branch B are different. It demonstrates how various tree branch components react differently to various vibrational frequencies. The structure of tree branches and the mechanical properties of tree materials are just two examples of the numerous elements determining how tree branches vibrate in response to various frequencies (*Liu et al., 2021*). Given that fruit trees have complicated structural and mechanical qualities as a result of their natural growing environment, it is impossible to ascertain the natural frequency of fruit trees in a timely manner. Therefore, using the resonance approach to efficiently harvest fruit is challenging.

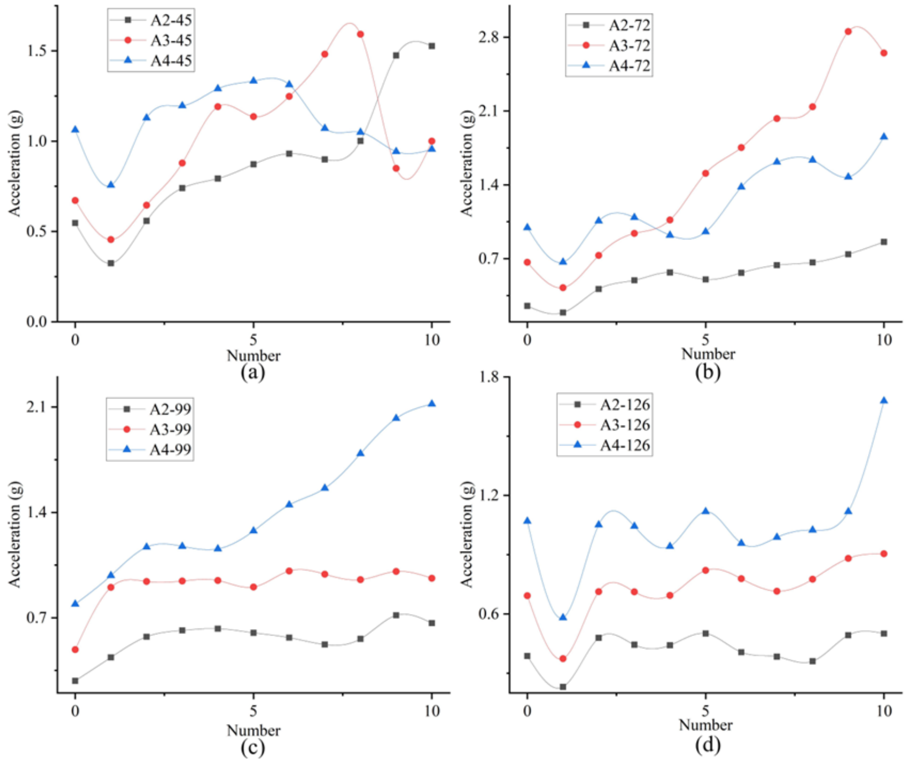

Fig. 10 - Influence of different vibration frequency on vibration response of A branch
(a): Clamping point G1; (b): Clamping point G2; (c): Clamping point G3; (d): Clamping point G4.

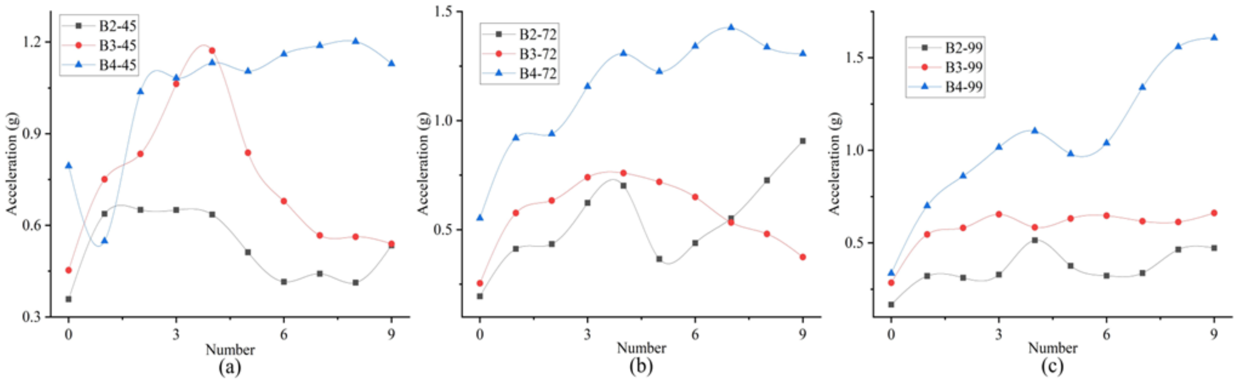

Fig. 11 - Influence of different vibration frequency on vibration response of B branch
(a): Clamping point G5, (b): Clamping point G6, (c): Clamping point G7.

Fig. 12 shows the relative kinetic energy ratio of each monitoring point of A branch to A1 monitoring point at different vibration frequency and Fig. 13 shows the relative kinetic energy ratio of each monitoring point of B branch to B1 monitoring point at different vibration frequency. High-frequency vibration can efficiently convey the vibration energy to the end of the branch when the clamping point is far from the tree trunk. When the clamping point is close to the tree trunk, high-frequency vibration makes it difficult to transfer vibration energy to the branch's end. At this time, the relative kinetic energy of monitoring point 0 is comparatively high, suggesting that more vibration energy is being transferred to the branch's base, causing in energy loss. This is because the branch's base has a considerable inhibitory impact on high-frequency vibrations, preventing the passage of high-frequency vibration energy from near the branch to the branch's end.

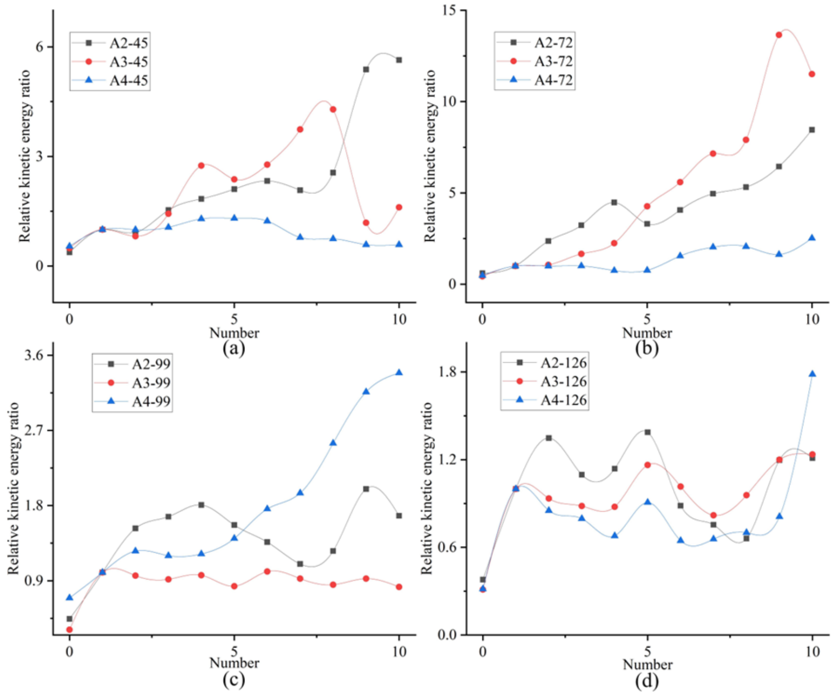

Fig. 12 - Influence of different vibration frequency on relative kinetic energy ratio of A branch
(a): Clamping point G1, (b): Clamping point G2, (c): Clamping point G3, (d): Clamping point G4.

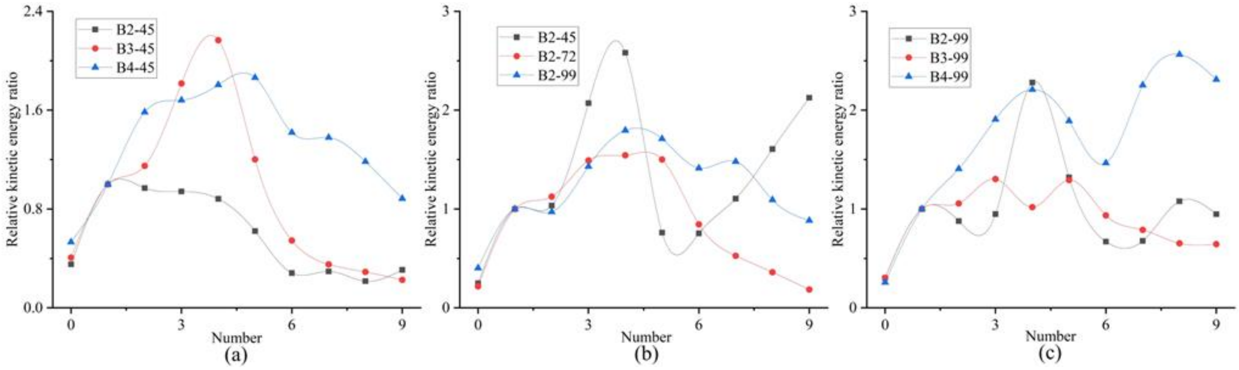

Fig. 13 - Influence of different vibration frequency on relative kinetic energy ratio of B branch
(a): Clamping point G1, (b): Clamping point G2, (c): Clamping point G3.

Influence on vibration response and relative kinetic energy ratio

Fig.14 shows the vibration acceleration and relative kinetic energy ratio of A branch monitoring point 10 under various influencing variables. Fig.15 shows the vibration acceleration and relative kinetic energy ratio of B branch monitoring point 9 under various influencing variables. To better display the effective kinetic energy transferred to the branch's end and the ineffective kinetic energy transferred to the branch's bottom, the relative kinetic energy ratio in Fig.14 is the ratio of the kinetic energy of monitoring point 10 to the kinetic energy of monitoring point 0, and the relative kinetic energy ratio in Fig.15 is the ratio of the kinetic energy of monitoring point 9 to the kinetic energy of monitoring point 0. From Fig.14, it is clear that the vibration acceleration and effective kinetic energy ratio are at their best when the clamping points are 72 cm apart, with a vibration frequency of 3 Hz. From Fig.15, it is clear that the vibration acceleration and effective kinetic energy ratio are at their best when the clamping points are 99 cm apart, with a vibration frequency of 4 Hz. In order to better reflect the relations between the clamping position and the length of the branch, divide the clamping distance by the total length of the branch. It is found that when the clamping position is 48%~73% of the overall length of the branch, a better ratio of the end acceleration and relative kinetic energy of the branch can be obtained. It's that the B branch at monitoring point 3 has a wide deflection angle, resulting in ineffective vibration energy transmission to the end of the B branch when it vibrates at the clamping position of G5. When the clamping position is G7, the deflection component of the B branch efficiently prevents vibration energy from passing to the branch's base along the B branch, enhancing total energy utilization. High-frequency vibration should be applied to the clamping part away from the trunk when the secondary branches are dispersing at the ends of the primary branches in order to maximize energy utilization and improve vibration responsiveness. When the secondary branches are evenly distributed on the primary branches, the clamping point should be in the middle of the primary branches.

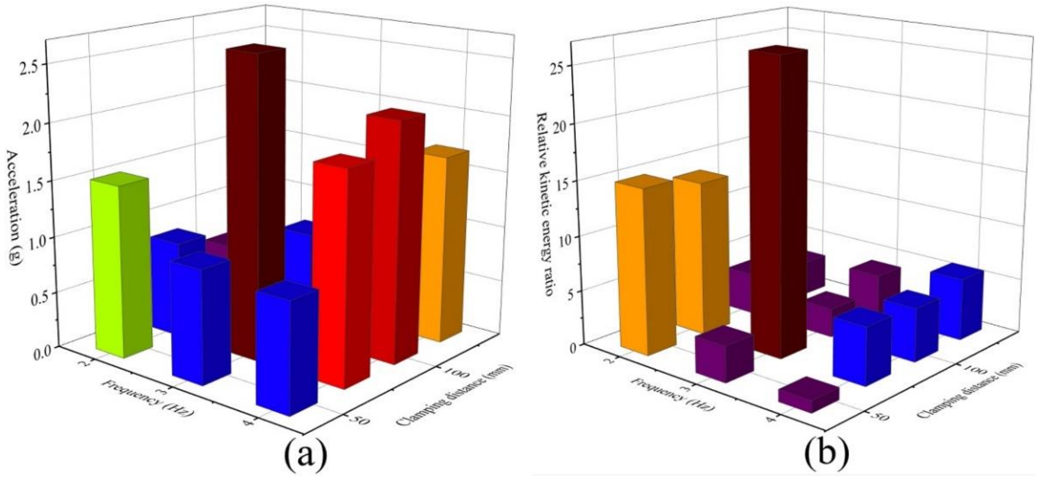

Fig. 14 - Influence of different factor on monitoring point 10 of A branch
(a): Acceleration of monitoring point 10, (b): Relative kinetic energy ratio of monitoring point 10.

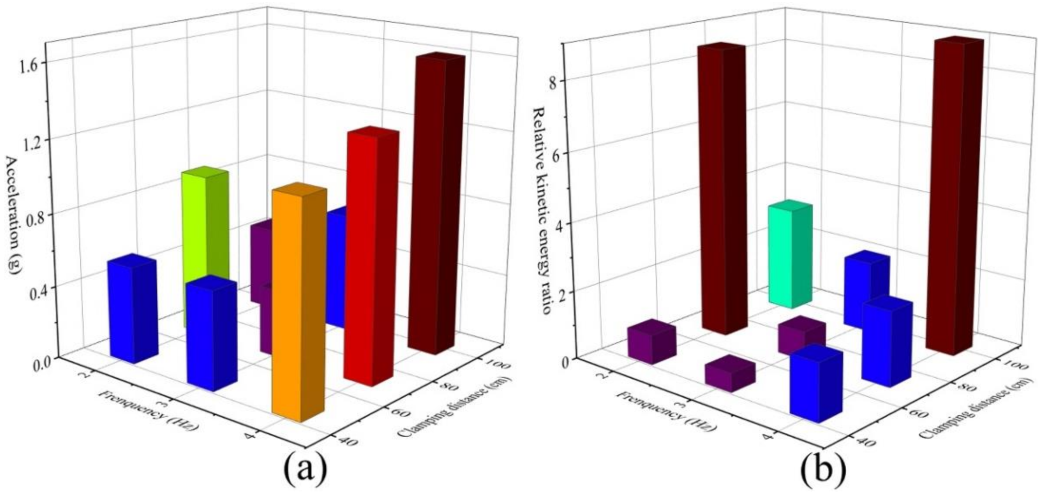

Fig. 15 - Influence of different factor on monitoring point 10 of B branch
(a): Acceleration of monitoring point 10, (b): Relative kinetic energy ratio of monitoring point 10.

CONCLUSIONS

According to the necessity and complexity of efficient vibration harvesting, this study used multiple vibration frequencies and vibration clamping positions to evaluate the vibration response and energy transfer efficiency of Broussonetia papyrifera branches. The conclusions are as follows:

(1) The vibration response of the part where the branch has a large deflection angle is greater than that of other parts of the branch, and this part can hinder the transmission of vibration energy.

(2) The ideal clamping distance should be between 48%~73% of the tree branches since it increases as the vibration frequency rises.

(3) The structural damping at the base of the branch has a more significant inhibitory effect on high-frequency vibrations than on low-frequency vibrations.

(4) When the clamping point is the middle part of the tree branch, the overall vibration response of the tree branch is better.

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