Dynamic characteristics of dwarf Chinese hickory trees under impact excitations for mechanical fruit harvesting

Du Xiaoqiang[1,2*], Wu Chuanyu[1,2], He Leiying[1], Tong Junhua[1]

(1. *School of Mechanical Engineering and Automation, Zhejiang Sci-Tech University, Hangzhou* 310018*, China*;
2. *Zhejiang Province Key Laboratory of Transplanting Equipment and Technology, Hangzhou* 310018*, China*)

Abstract: Mechanical vibration is an effective fruit harvesting method. To evaluate the dynamic characteristics of dwarf Chinese hickory (*Carya cathayensis* Sarg.) trees and the influence of the tree structure on transmission and attenuation of dynamic response, a new method was proposed based on acceleration admittance measurement on dwarf Chinese hickory trees in orchard environment under impact excitation. The primary resonance frequencies of the tree can be determined based on the acceleration admittance measurement. The effect of the tree structure on the vibratory transmission was quantified using the attenuation ratio of the acceleration admittance. A 5-year-old dwarf Chinese hickory tree sample was tested. The responses at three resonance frequencies (5, 9 and 12 Hz) were analyzed because they were identified as the most effective bands of excitation for the main part of the tree specimen. The results reveal that the variation of the dynamic response along the testing tree is greatly related to the Chinese hickory tree structure. The attenuation ratio of the acceleration admittance at the branch crotches indicates the leader top crotch may amplify the acceleration admittance no matter what the crotch angle and the branch diameter is. Unlike the crotches, the branch chain nodes generally have negative influence on the acceleration admittance along the branch chains which heavily depend on the branch chain configuration. The branch chains with a chain angle no less than 150° and a wood diameter ratio close to 1.0 could produce little influence on the vibration transmission. For those branches with chain angle less than 150°, the vibration was generally attenuated at their chain nodes at three resonance frequencies. To impose impact excitations on the tree, high mechanical harvesting efficiency could be achieved on those branch chains which are almost straight and uniform.

Keywords: Chinese hickory, mechanical harvest, fruit, acceleration admittance, vibration transmission, impact test
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1 Introduction

Chinese hickory (*Carya cathayensis* Sarg.) has been cultivated commercially in northwestern of Zhejiang Province and southeastern of Anhui Province in China for about 500 years. The planting area is about 87 100 hectares at present. The nuts list high nutrition value and health benefit. The output value of the Chinese hickory nut was more than 2.5 billion Chinese Yuan in Zhejiang Province in 2011, which accounted for 90% output value of China[1]. Most trees are wild and growing to 18 m high at a slow rate, and generally grow on the steep mountainside, which makes it difficult or even dangerous to harvest Chinese hickory nuts[2]. Many machines have been developed for tree fruit harvesting. However, none of them was made commercially due to its inefficiency[3]. The same problem exists in Chinese hickory harvesting. The

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Biographies: Wu Chuanyu, PhD, Professor, majoring in agricultural machinery, robotics technology and mechanical design. Email: cywu@zstu.edu.cn. **He Leiying**, PhD, majoring in machine vision and agricultural machinery. Email: heleiying@163.com. **Tong Junhua**, PhD, majoring in machine vision and agricultural machinery. Email: jhtong@zstu.edu.cn.
***Corresponding Author: Du Xiaoqiang**, PhD, Associate Professor, majoring in agricultural machinery, robotics technology and mechanical design. Address: Faculty of Mechanical Engineering and Automation, Zhejiang Sci-Tech University, Xiasha College Park, Hangzhou, Zhejiang 310018, China. Tel: +86-571-86843347. Email: xqiangdu@zstu.edu.cn.

worker has to climb up the tree and beat the fruiting branch with a bamboo rod. Falling accidents always occur each year during the harvest season. It was reported that nine people died during harvesting the Chinese hickory nuts in Zhejiang Province in 2011. It is of great significance to design a mechanical harvester for Chinese hickory tree. And shaking/vibratory methods should be the most appropriate way for mechanically harvesting Chinese hickory because of large size of trees and scattered distribution of nuts.

During shaking, a tree will respond differently to different excitation frequencies, and vibratory fruit removal normally occurs when the detachment force exceeds the pedicel-fruit tensile force[4]. For designing Chinese hickory harvester, it is important to study the dynamic behavior of Chinese hickory tree under dynamics excitations. Many investigations of tree dynamics have been carried out based on either experimental data or model analysis. Fridley and Lorenzen[5] developed a model of four degrees of freedom lumped mass system to analyze the tree shaking. Cooke and Rand[6] proposed a linearized three degrees of freedom model of a fruit-stem system and analyzed the tree responses under sinusoidal vibrations by this model. Tsatsarelis[7] adopted this model to analyze the fruit removing actions for olive harvest. Upadhyaya et al.[8] created a single degree of freedom model to describe the impact response of a tree and found only some impact energy could be transferred to the tree. Hussain et al.[9] studied tree limb response to a periodic discontinuous sinusoidal displacement and revealed that higher accelerations induced by the impact of a non-clamped shaker on the limbs would be more effective in fruit removal. Phillips et al.[10] modeled tree limbs with secondary branches as uniform Euler-Bernoulli beam elements with lumped mass at nodal points and simulated their forced vibration by finite element analysis. Yung and Fridley[11] established an entire tree model using linearly tapered elements based on finite element analysis. Savary et al.[12] studied the dynamic responses of the citrus trees using the finite element simulation approach. Du et al.[13] used an electro-dynamic shaker to carry out a series of experiments on sweet cherry trees with UFO architecture under vibratory excitations in laboratory and field test to explore the dynamic responses and identify the resonant frequencies of trees by seeking the peak displacement of limbs under different vibration frequencies.

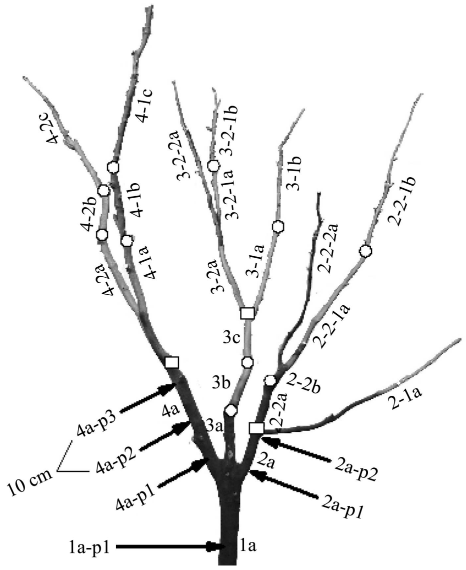
The basic principle of vibratory harvest is to transmit vibratory energy to fruiting branches and then convert the energy to a detaching force on fruit-stems[14]. Previous studies indicate that trees respond to the vibratory excitation in different patterns. However, few investigations have been carried out to describe the distribution and dissipation of the vibration along the tree branch chains, which is useful to find the best vibratory excitation mode (location, frequency, and amplitude) and then design a mechanical harvester to provide the appropriate excitation. Recently, a dwarfing technique for Chinese hickory tree has been developed which could control growth height, increase fruiting branches and advance fruiting age. This makes it convenient to investigate the vibration transmission along the trees. The main purpose of this paper is to propose a new method to investigate the dynamic transmission of vibration along the dwarf Chinese hickory trees under impact excitations and to assess the branch crotches and nodes related to the tree structure to evaluate their effect on the vibration transmission based on the method.

2 Materials and methods

2.1 Experimental materials and impact testing system

The dynamic response experiment was conducted on March 27-29, 2012 at a Chinese hickory experiment orchard located at Lin'an County, Zhejiang Province, China. The temperature was around 15-18℃. The trees in the cultivation base has been grafted and dwarfed, which generally grow up to 5 m and start to bear fruit from the third year after they were planted. During each experiment there was no wind influencing the trees.

Therefore, a 5-year-old dwarf Chinese hickory tree was randomly selected as the experiment sample. It consists of a trunk with three leaders and several branches and limbs, as shown in Figure 1. There are many small twigs at the apex of the tree crown. Due to their small size, only the major part of the tree was measured during the following experiment.



Note: The numbering system is so defined that the first number *i* represents the order of the trunk or leader limbs; the second number *-j* represents the order of the secondary branches/limbs growing from the leader limbs; the third number *-k* represents the order of the subordinate branches/limbs growing from the secondary branches; the alphabetic word represents different branches in a branch chain; and *-pm* indicates a monitoring position on a branch; the square represents the crotch node; the circle represents the chain node

Figure 1 Illustration of geometric model for testing Chinese hickory tree

Therefore, the sample tree structure can be divided into four main sections: the trunk, the leader limbs, the secondary branches which grow from the leader limbs (branch-on-leader), and the subordinate branches and twigs growing from the secondary branches (branch-on-branch). For clarity, the trunk is indexed as 1 and three leader limbs are indexed as 2, 3, and 4, respectively. The subordinate branch or branch chain is indexed by adding a number to the index of the corresponding superior branch or branch chain. Each branch in the branch chains is indexed by suffixing an alphabetic word to the corresponding branch chain index. The major branch indexes and their geometric dimensions are listed in Table 1. The wood diameter was measured by vernier caliper with its precision of 0.02 mm. Two intersectant branches forms a crotch feature characterized as a crotch angle between the branches and a crotch node marked by a white square in Figure 1. Two successive branches forms a chain feature characterized as a chain angle between two successive branches and a chain node marked by a white circle in Figure 1.

Table 1 Major branches indexes, geometric dimensions and monitoring locations of Chinese hickory tree sample illustrated in Figure 1

Branch index	Length /m	Average diameter/mm	Category	Monitoring location
1a	0.93	43	trunk	1a
2a	0.11	23	leader limb	2a-p1, p2
2-1a	0.71	10	branch-on-leader	2-1a-p1,…, p5
2-2a	0.11	20	branch-on-leader	2-2a-p1, p2
2-2b	0.07	17	branch-on-branch	2-2b-p1
2-2-1a	0.34	13	branch-on-branch	2-2-1a-p1,…, p4
2-2-1b	0.47	8	branch-on-branch	2-2-1b-p1,…, p4
2-2-2a	0.56	8	branch-on-branch	2-2-2a-p1,…, p4
3a	0.11	25	leader limb	3a-p1, p2
3b	0.13	21	leader limb	3b-p1, p2
3c	0.12	20	leader limb	3c-p1, p2
3-1a	0.33	13	branch-on-leader	3-1a-p1,…, p4
3-1b	0.21	10	branch-on-branch	3-1b-p1, p2, p3
3-1c	0.16	8	branch-on-branch	3-1c-p1, p2
3-2a	0.21	15	branch-on-leader	3-2a-p1, p2, p3
3-2-1a	0.35	12	branch-on-branch	3-2-1a-p1,…, p4
3-2-1b	0.14	9	branch-on-branch	3-2-1b-p1
3-2-2a	0.57	7	branch-on-branch	3-2-2a-p1,…, p4
4a	0.24	27	leader limb	4a-p1, p2, p3
4-1a	0.34	19	branch-on-leader	4-1a-p1,…, p4
4-1b	0.19	14	branch-on-branch	4-1b-p1, p2
4-1c	0.27	11	branch-on-branch	4-1c-p1, p2, p3
4-2a	0.37	20	branch-on-leader	4-2a-p1,…, p5
4-2b	0.12	17	branch-on-branch	4-2b-p1, p2
4-2c	0.22	17	branch-on-branch	4-2c-p1, p2

Figure 2 shows the impact testing system in the form of a schematic diagram. During the experiment, an impact hammer (Model 086C03, PCB Piezotronics, Depew, NY, USA; mass: 0.16 kg; sensitivity: 2.25 mV/N; frequency range: 8 kHz; measurement range: ±2 224 N) was used to provide impulsive shocks having wide bandwidth frequency. The hammer is equipped with several hammerheads suitable for different effective frequency bandwidth from zero to several thousand Hz. In the impact excitation experiment, the frequency analysis bandwidth of the tree specimen response was set to 300 Hz. Rubber hammerhead was used to boost the effective bandwidth vibration up to 600 Hz. The impact force was exerted on the trunk at 0.43 m below the junction (Point 1a-p1 in Figure 1). And the force was measured by the force sensor assembled on the impact hammer when the hammer hit the tree. An accelerometer (Model 356A16, PCB Piezotronics, Depew, NY, USA; mass: 7.4 g; sensitivity: 100 mV/g; frequency range: 0.5 Hz to 5 kHz; measurement range: ±50 g) was mounted on the monitoring locations of the tree specimen with nylon ribbon to obtain the acceleration responses, as shown in Figure 3. After the response of one monitoring location was recorded, the accelerometer was moved to the next monitoring location. To decrease the measurement error, the hammer impacted the tree at the excitation point four times when measuring the response at one monitoring location. After the tree was impacted once, the next impact was not applied until the tree resumed immobility. The response at one monitoring location was the averaged measurement response during four times impact. Those measuring positions were set 10 cm apart on each branch started from the corresponding crotch node or transition node. Although the accelerometer can measure triple-axis accelerations, the axis parallel to the direction of impact excitation was recorded as the dynamic response in this direction was remarkably stronger than other two directions. A data acquisition and analysis system (Model AVANT MI-7008, ECON Technologies, Hangzhou, Zhejiang, China; input channel: 8; output channel: 2; digital/analogical filter; sampling frequency: 192 kHz; SNR: >100 dB; frequency accuracy: 0.0075%) was used to record the excitation and the responding acceleration signals.

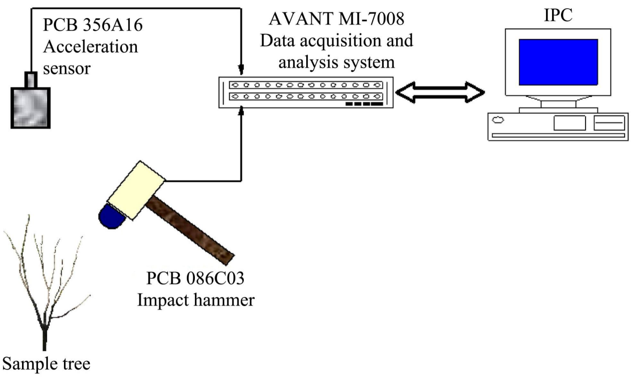


Figure 2 Schematic diagram of the test control and data acquisition setup

Figure 3 Photography of the sensors mounted on the tree

2.2 Vibratory transmission path and mechanical admittance analysis

To analyze the vibration transmission in a tree, the vibratory transmission path can be considered as from the excitation point through the intermediate branches to each terminal branch. According to the structure of the tree specimen, there are eight transmission paths starting from the excitation point to the targeted fruiting branches, numbered path I to path VIII, as shown in Figure 4.

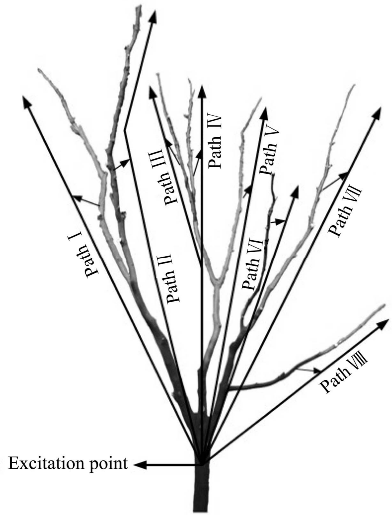


Figure 4 Definition of eight vibratory transmission paths on the tree specimen

During the vibratory excitation, different parts of the tree had different dynamic response to the excitation, which was due to the mechanical admittance of each location in nature. Mechanical admittance is a measure of how much a structure moves when subjected to a given force[15]. The mechanical admittance of a point on a structure is the ratio of the resulting motion (displacement, velocity or acceleration) at that point to the force applied at a point. Therefore, the mechanical admittance from the excitation point to each monitoring location could be considered as the dynamic response taken by the monitoring location per unit excitation force exerted at the excitation point. Furthermore, the mechanical admittance, which is derived from a Fourier analysis of the force and dynamic response signals, is a function of the frequency of the applied force and can vary greatly over frequency. At resonance frequencies, the mechanical admittance will be higher, meaning stronger response will be inspired under the same excitation force.

In this paper, the resonance frequencies of each vibratory transmission path on the tree sample are identified based on the acceleration admittance of each monitoring location. These paths are compared to investigate the influence of tree structure on the dynamic properties of the dwarf Chinese hickory tree.

Branch junctions including crotches and nodes are important influence factors on vibratory energy transmission[13]. To describe the dynamic response changes at the crotch or chain nodes more illustratively, an attenuation ratio of acceleration admittance is defined using Equation (1).

$$r_{ij}=1-a_j/a_i \tag{1}$$

where, r_{ij} is the attenuation ratio of acceleration admittance at a crotch or chain node; i, j represent the close-by monitoring location on the branch growing before and after a crotch or chain node, respectively; and a_i, a_j are the acceleration admittance at the corresponding location.

The attenuation ratio of acceleration admittance at the resonance frequencies along the tree sample was analyzed. Two structure features (the crotch and chain nodes) were discussed to further determine the influence of tree structure on the transmission of the dynamic response. The following parameters were evaluated:

1) The feature angle including the leader top crotch angle, and the chain angle;

2) The wood diameter ratio at each discussed feature, as the ratio between the branch section diameter at the monitoring locations before and after the corresponding feature along the vibratory transmission path.

Comparing mechanical admittance of different paths could provide a practical means for analyzing the influence of the tree structure on transmission and attenuation of dynamic response, and also offer a base for evaluating the potential efficiency of vibratory harvest.

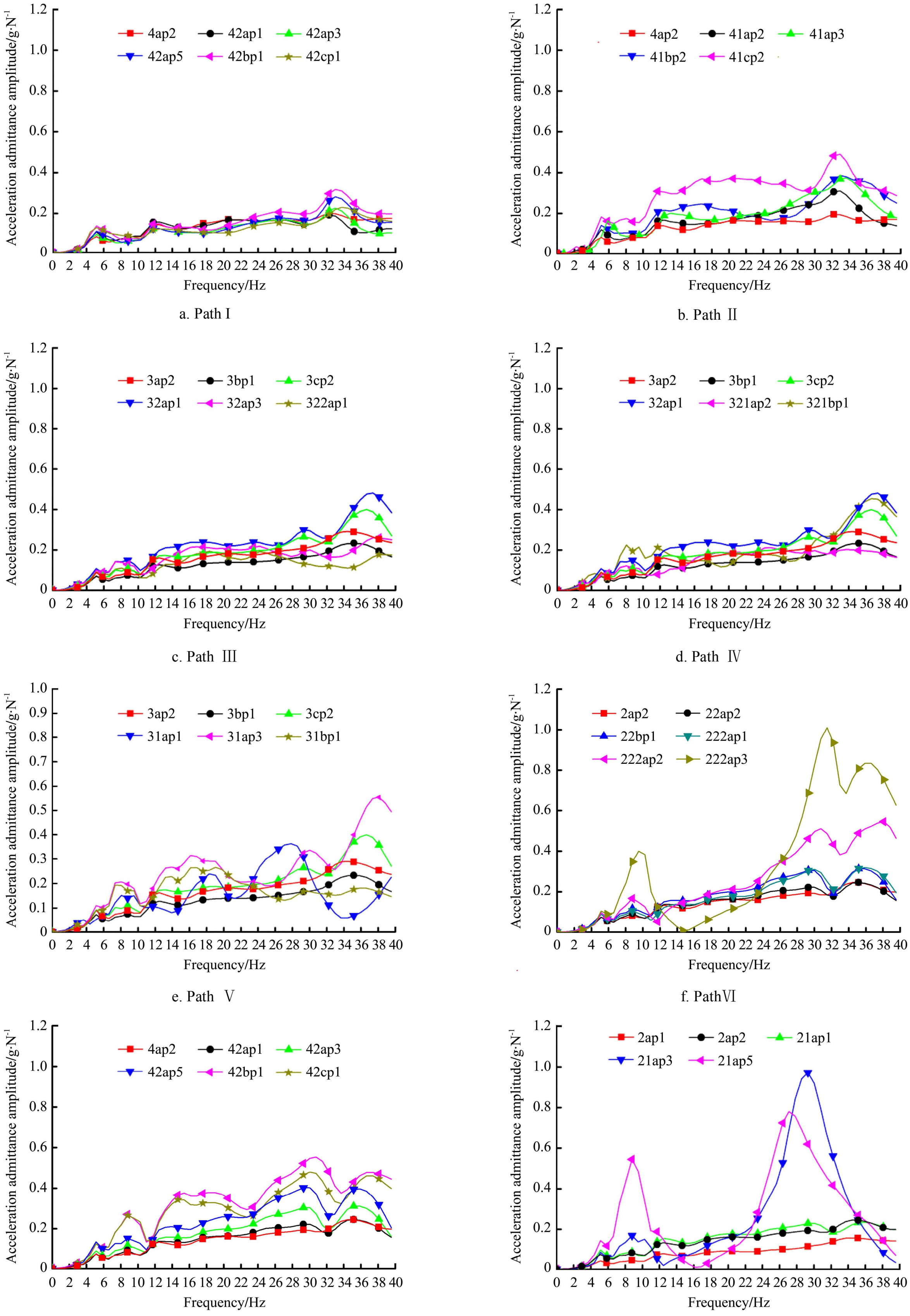
3 Results and discussion

3.1 Identification of resonance frequencies

Because tree generally grows into the branch-on-branch structure, tree vibration excited by the external force distributes unevenly on different parts of the tree[16]. Therefore, under each impact excitation, branches on the tree specimen did not vibrate in the same amplitude and direction. The resonance frequencies of each branch were found different. However, the main part of the tree presented the similar components of resonance frequency which could be considered as the tree's resonance frequencies.

Figure 5 shows the dynamic response of the testing Chinese hickory tree. The acceleration admittance amplitude of the monitoring locations on path I and path II is presented in Figure 4a and Figure 5b, respectively. Two paths have a common leader limb 4a and a crotch angle of approximate 30° between the branch-on-leader 4-1a and 4-2a, as shown in Figure 1. Obtained results indicates that the resonant responses on paths I and II occur at around 5, 12, and 33 Hz except that the admittance amplitude of the monitoring location on the branch 4-1c is much higher. This is likely attributed to the chain angle of more than 150° between the branch 4-1b and 4-1c because the chain angles between any pair of other successive branches are no less than 150° in these two paths.

Paths III, IV, and V have a common leader limb and an approximate 30° crotch angle. There is a secondary crotch on top of the branch-on-leader 3-2a with a crotch angle of approximate 70°. Paths VI, VII, and VIII have the same shape as paths III, IV, and V except that the crotch growing from the leader limb 2a has an angle approximate to 80° and the secondary crotch on top of the branch-on-leader 2-2b has an angle of approximate 60°, as shown in Figure 3. The chain angles on each path are no less than 150°. Figures 5c-5h show the acceleration admittance amplitude of the monitoring locations on those paths. Although different monitoring locations along those paths display different acceleration admittance amplitudes, their frequency responses could be divided into two groups, i.e., the response of the leader limbs and that of the offshoots of the crotch. As shown in Figures 5c-5h, the responses of the leader limbs on those paths all go up to their local peaks at around 5, 9, 12, 30, and 34 Hz, which are in part accordance with the resonance frequencies of the leader limb on paths I and II. However, the response of the offshoots of the crotch on each path has their resonance frequencies different from those of the leader limbs. But the resonance frequencies of those offshoots with a subordinate crotch are very close to those of the leader limbs, as shown in Figures 5c, 5d, 5f and 5g. The shift of the resonance frequencies could be attributed to the subordinate crotch.



a. Path I b. Path II

c. Path III d. Path IV

e. Path V f. Path VI

g. Path VII h. Path VIII

Figure 5 Acceleration admittance amplitude curves of different monitoring locations on the vibratory transmission path I, path II, path III, path IV , path V, path VI, path VII, and path VIII of the testing tree under the impact excitations

Figures 5e and 5h show that the acceleration admittance of those offshoots without a subordinate crotch presents their local peaks at quite different frequencies because they are much lighter compared with other offshoots. Those heavy offshoots form the main part of the tree and are crucial to the tree's resonance frequencies.

3.2 Analysis of the variation of acceleration admittance

To analyze the variation of the acceleration admittance along each vibratory transmission path under impact excitation, Equation (1) was used to determine the attenuation ratio of the acceleration admittance at each crotch or chain node on different paths. Only responses at three resonance frequencies (5, 9 and 12 Hz) were analyzed because they were identified as the most effective bands of excitation for the main part of the tree specimen. The responses at each crotch or chain node were compared to find out the influence of the crotch or chain angle and the branch diameter on the acceleration admittance based on the results in Tables 2 and 3. Table 2 shows the attenuation ratio of the acceleration admittance at three resonance frequencies obtained from the responses of the crotches on top of three leader limbs (2a, 3c, 4a). The acceleration admittance of the adjacent monitoring location on the branch growing from the crotch is generally greater than that of the adjacent monitoring location on the branch before the crotch at the position (Figure 1). This indicates that as the principal structure of the tree, the leader top crotch may result in certain amplification on the vibration transmission along the path. However, the amplification has no relation with the crotch angle and the branch diameter based on the obtained results. As shown in Table 2, the crotch formed by the branches 3-1a, 3-2a has a crotch angle and wood diameter ratio similar to the crotch formed by the branches 4-1a, 4-2a. When the tree trunk is subject to an external excitation at the resonance frequencies, the vibration passing the crotch between 3-1a and 3-2a is amplified by almost 30%-70%, and the amplification of the vibration passing the crotch between 4-1a and 4-2a is less than 10%.

Table 2 Obtained attenuation ratio of acceleration admittance at the leader top crotches at the principal resonance frequencies (5, 9, 12 Hz)

Monitoring location i	Monitoring location j	Crotch angle	Wood diameter ratio	Acceleration admittance attenuation ratio at resonance frequency		
				5 Hz	9 Hz	12 Hz
2a-p2	2-1a-p1	≈80°	0.4312	-0.3044	-0.1602	-0.1458
	2-2a-p1		0.8885	-0.0901	-0.0958	-0.0749
3c-p2	3-1a-p1	≈30°	0.6426	-0.3407	-0.6073	-0.4955
	3-2a-p1		0.7563	-0.2880	-0.6918	-0.3872
4a-p3	4-1a-p1	≈30°	0.7019	-0.0645	-0.0124	-0.0519
	4-2a-p1		0.8030	-0.0359	-0.1053	-0.1094

Table 3 Obtained attenuation ratio of acceleration admittance at the branch chains at the principal resonance frequencies (5, 9, 12 Hz)

Monitoring location i	Monitoring location j	Chain angle	Wood diameter ratio	Acceleration admittance attenuation ratio at resonance frequency		
				5 Hz	9 Hz	12 Hz
3b-p2	3c-p1	>150°	0.9832	-0.0636	-0.2434	0.0080
4-2a-p5	4-2b-p1	≈150°	0.9429	0.0253	-0.0852	0.0410
3-2-1a-p4	3-2-1b-p1	>150°	0.9110	0.0703	0.1458	0.0725
3-1a-p4	3-1b-p1	>150°	0.8973	0.4878	0.2678	0.4131
2-2a-p2	2-2b-p1	≈150°	0.8653	0.2571	0.0188	0.2261
2-2-1a-p4	2-2-1b-p1	≈150°	0.7948	0.2360	-0.0133	0.5540
4-1b-p2	4-1c-p1	>150°	0.8042	-0.2801	-0.1001	-0.1767
3a-p2	3b-p1	<150°	0.8921	0.1818	0.1238	0.1416
4-1a-p4	4-1b-p1	<150°	0.9046	0.0753	0.1431	-0.4083
4-2b-p2	4-2c-p1	<150°	0.9165	0.4099	0.4174	0.4721

Significant influence of the chain nodes was observed on the acceleration admittance of the successive branches. Table 3 shows the acceleration admittance attenuation ratio at seven main chain nodes at three resonance frequencies. These nodes feature different chain angle and wood diameter ratio which could be divided into three groups:

1) The branch chains of 3b, 3c, and 4-2a, 4-2b both have a chain angle no less than 150° and a wood diameter ratio close to 1.0, which show quite low acceleration admittance attenuation ratio at the resonance frequencies. These chain nodes could be considered as producing little influence on the vibration transmission along the branch chains which are almost straight and uniform.

2) The chain angle in the branch chains of 2-2a, 2-2b, 3-1a, 3-1b, 4-1b, 4-1c, 2-2-1a, 2-2-1b, and 3-2-1a, 3-2-1b is also no less than 150° while the wood diameter difference between the adjacent branches is more than

10%. The vibration at the resonance frequencies is generally damped by these chain nodes where the acceleration admittance attenuation ratio is mostly positive except that the node between branch 4-1b and 4-1c results in certain amplification at three resonance frequencies and the node between branch 2-2-1a and 2-2-1b amplifies a little at 9 Hz.

3) For those branches with chain angle less than 150° (branches 3a, 3b, 4-1a, 4-1b, 4-2b, 4-2c), the acceleration admittance attenuation ratio at these chain nodes is mostly positive at three resonance frequencies except that the node between 4-1a and 4-1b results in amplification at 12 Hz.

Therefore, the vibration transmission along the branch chains heavily depends on the branch chain configuration and is generally attenuated at the chain nodes. These results underscore the role of the branch chain configuration at affecting the vibration transmission, and potentially, the mechanical harvest efficiency because the primary fruiting branches usually form the chain features.

4 Conclusions

An impact test was conducted to advance knowledge of key components needed for developing a high performance mechanical harvester for Chinese hickory tree. The dynamic characteristics of the leader limbs and heavy offshoots determined the tree's dynamic behavior and their resonance frequencies were identified as the tree's resonance frequencies based on the acceleration admittance measurement and analysis.

The influences of tree architecture on dynamic behaviors were demonstrated in this study. The attenuation ratio of the acceleration admittance at each crotch or chain node on different paths was defined to quantitatively analyze the vibration transmission under impact excitation. The responses at three resonance frequencies (5, 9, and 12 Hz) at each crotch or chain node were compared to find out the influence of the crotch or chain angle and the branch diameter on the acceleration admittance. Results obtained from this study reveal that vibration transmission pattern is heavily related to Chinese hickory tree structure. The leader top crotch may amplify the acceleration admittance, while the amplification has no relation with the crotch angle and the branch diameter. The acceleration admittance along the branch chains is generally attenuated at the chain nodes and heavily depends on the branch chain configuration. High mechanical harvesting efficiency could be achieved on those branch chains which are almost straight and uniform.

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