RESEARCH ON THE VIBRATION AND FRUIT DROP CHARACTERISTICS OF CAMELLIA OLEIFERA BASED ON HIGH-SPEED PHOTOGRAPHY TECHNOLOGY /

基于高速摄影技术的油茶振动落果特性研究

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ABSTRACT

This study employed high-speed photography to reproduce the vibration behavior of Camellia oleifera fruit and flower buds. Vibration energy was transmitted through the branches to break the balance of the Camellia oleifera branch system, causing the fruit and flower buds to exhibit anisotropic chaotic swings. Post-processing of images showed that the fruit detachment force ranged from 4.57 to 11.85 N, and the flower bud detachment force ranged from 0.68 to 3.24 N. At a vibration frequency of 12.98 Hz, the vibration amplitude did not have a significant effect on the detachment force of fruit and flower buds. The detachment time of Camellia oleifera fruit and flower buds decreased with the increase of vibration amplitude or excitation frequency. Through fitting and analysis of the collected data, the Fourier fitting curves and functions of the motion acceleration of oil-tea fruit and flower buds were obtained, with R^2 values of 0.83996 and 0.73718, respectively.

摘要

通过高速摄影还原了油茶果实与花苞振动行为，振动能量经枝干传递打破枝条系统平衡，使其呈各向异性混沌摆动。后处理影像显示，果实脱落力4.57~11.85N、花苞0.68~3.24N，12.98Hz振动下幅值对脱落力影响不明显，脱落时间随幅值或频率增加而减少。经数据拟合得果实、花苞运动加速度傅里叶拟合曲线及函数，R^2分别为0.83996、0.73718。

INTRODUCTION

Camellia oleifera, a tree species lacking a distinct main trunk, is well-suited for mechanical harvesting of its fruits using canopy vibrators *(Du et al., 2024; Wu et al., 2022; Zhang et al., 2020)*. Compared to manual picking, mechanical harvesting equipment significantly reduces production costs. Mechanical vibration devices apply excitatory forces to fruit trees, inducing synchronized vibration of fruits through branch movement. When the inertial force of a fruit exceeds the binding force between the fruit and its stalk, the fruit detaches *(Freitas Grupioni et al., 2020; Juan et al., 2020; Zhou et al., 2022)*.

Current research on fruit abscission faces a key limitation: most studies rely on physical experiments and theoretical models *(Tombesi et al., 2017; Wu et al., 2020a; Brondino et al., 2021)*, primarily measuring static detachment forces between fruits and stalks. Dynamic analysis of real-time abscission forces under forced vibration remains scarce. While some researchers use physical sensors (e.g., accelerometers) to monitor target motion during tree vibration—requiring sensor placement on fruits or branches to measure acceleration responses under excitation *(Castro-Garcia et al., 2017; Niu et al., 2022; Yuan, 2022; Wu et al., 2020b)*—others have detected through trunk/fruit sensors that fruit drop frequency correlates with vibrator frequency, with resultant acceleration values dependent on fruit-vibrator system interactions *(Torregrosa et al., 2014; Juan et al., 2020; Sargent et al., 2020)*. Though these sensor-based methods efficiently capture motion response patterns, they inherently alter the physical properties of the original branch-fruit system. The added mass and mechanical interference from sensors introduce uncertainties into experimental results.

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Non-contact measurement technologies offer a solution to these limitations. High-speed photography (HSP) and image processing *(Torregrosa et al., 2014; Xu et al., 2019)* enable precise, contact-free reconstruction of fruit motion during forced vibration. By recording the instantaneous process of fruit-stalk separation with HSP and analyzing key parameters (displacement, velocity, acceleration) via post-processing software, researchers can characterize dynamic behaviors of fruits under vibration and deepen mechanistic understanding of abscission.

This study employs high-speed photography to capture dynamic changes in Camellia oleifera fruits and flower buds during vibration, documenting their abscission timing and modes. Through video data processing, movement trajectories are quantified and vibration-responsive characteristics are analyzed, providing a theoretical basis for optimizing vibrator-based harvesting equipment parameters.

MATERIALS AND METHODS

This study utilized dwarf *Camellia oleifera* trees cultivated in Hunan Province, China, with "Xianglin" fruit varieties as the experimental material. The experiments were conducted in November 2024, corresponding to the mature and optimal harvest period of the "Xianglin 210" cultivar. Branches bearing both fruits and flower buds were excised from the trees and transported to the laboratory for vibration testing.

Excitation device

In the mechanical picking process, regardless of the excitation method employed, vibration energy is transmitted from the branches to the fruits. When the inertial force of the fruits reaches the binding force, the Camellia oleifera fruits will fall off. The experimental test uses a crank - connecting rod - slider mechanism as the vibration energy source (as shown in Figure 1). The vibration frequency of the excitation device can be continuously adjusted within the range of 0 – 30 Hz, and the excitation amplitude values are available in size specifications of 10 mm, 20 mm, 50 mm, and 100 mm. The excitation device is fixed on the small lifting platform to adjust the height of the excitation position. At the same time, a specific clamping mechanism is designed at the end of the slider. Theoretically, the acceleration of the excitation device can be obtained through the following formula:

$$a = \frac{dv}{dt} = -\omega^2 R \sin\left(\omega t + \varphi\right) \tag{1}$$

The maximum absolute value in this case:

$$Abs\left(a_{\max}\right) = \omega^2 R = \left(2\pi f\right)^2 R \tag{2}$$

where: t — time, [s];
R — the length of the crank, [m];
ω — the angular velocity, [rad/s];
f — the frequency, [Hz];
φ — the phase, [rad];
v — the linear velocity, [m/s];
a — the acceleration, [m/s^2].

The theoretical values of the parameters at different amplitudes and frequencies are compared with the results of video analysis.

Image acquisition and analysis

The images were captured using a high-speed industrial camera (resolution: 1920(H)×1080(V); 2.0 megapixels; Model: L-PRI 1000; Exposure time: 2 μs/frame rate; AOS Technologies AG), along with a computer, Phantom control software, and data analysis and processing software.

Data analysis and processing software was employed to analyze the motion states of Camellia oleifera fruits and buds. Using the center of the target fruit or bud as the origin, the position of the tracked fruit or bud was collected every 0.02 seconds. The acceleration of fruits and buds during the forced vibration of Camellia oleifera branches was calculated using the following acceleration formula:

$$a = \frac{v}{t} = \frac{x}{t^2} \tag{3}$$

where:

a — the acceleration, [m/s^2];

v — the velocity, [m/s];

t — the interval between two adjacent photos, which is 0.02 s;

x — the relative displacement of the fruit in the two pictures, [m].

By measuring the quality of the fruit and bud, you can know the size of the inertia force when the fruit and bud fall off. The inertia force when falling off is:

$$\begin{cases} F_g = m_g a_g \\ F_h = m_h a_h \end{cases} \tag{4}$$

where: F_g — the inertial force when the fruit falls off, [N];

F_h — the inertial force when the bud falls off, [N];

m_g — fruit mass, [kg];

m_h — bud mass, [kg];

a_g — the acceleration of fruit shedding, [m/s^2];

a_h — the acceleration when the bud falls off, [m/s^2].

Test

The slider's end is fixed to the Camellia oleifera stem, with the fixed point located 100 mm away from the fixture (Fig. 1).

Fig. 1 - Vibration test device

During the test, the excitation amplitude is regulated by altering the connecting rod's position on the crank, while the excitation frequency is adjusted by using a frequency modulator to control the motor speed. In each test run, after setting the excitation frequency and amplitude, the clamp is used to secure Camellia oleifera branches under laboratory conditions. Specifically, the branch samples are clamped onto the fixture to ensure they form a specific angle with the vibration platform, simulating the natural growth posture of branches on the tree. Subsequently, the motor is activated, and a high-speed camera records the motion response of Camellia oleifera fruits under forced vibration.

RESULTS AND DISCUSSION

Vibration exciter movement analysis

According to the method given, the video in high-speed photography is analyzed frame by frame and the actual acceleration is calculated. Comparing these accelerations with the theoretical calculations results in very close values (Tab.1). The maximum relative error between the theoretical value and the actual value of the output acceleration of the exciter is 1.84%, and the parameter combination at this time is the excitation frequency of 2.05 Hz and the amplitude of 10 mm. It shows that the moving image acquired by high-speed photography base is reliable after post-processing.

Table 1

Vibration transfer efficiency with different parameters

Amplitude [mm]	Frequency [Hz]	Vibration exciter output acceleration [m/s^2]		error [%]
		Theoretical value	Actual value	
10	2.05	1.66	1.63	1.84
20	7.52	44.61	44.35	0.59
50	12.98	332.23	333.52	0.39

Impact analysis of vibration parameters

Through analysis of the high-speed video, the shedding force of Camellia oleifera fruit was found to range from 4.57N to 11.85N, while that of buds ranged from 0.68N to 3.24N. These values are significantly lower than the binding force measured via static testing of Camellia oleifera fruit *(Wang et al., 2024)*. This phenomenon can be attributed to the following: during static measurement of the fruit-stalk binding force, the fruit was pulled vertically along the stalk. In contrast, high-speed photography revealed that during vibration, the fruit-stalk exhibited a certain swing angle relative to the branch — indicating that the shedding force of the fruit-stalk varies with different angles of application.

Table 2

Effects of vibration parameters on fruit and bud shedding of *Camellia oleifera*

Amplitude [mm]	Frequency [Hz]	Fruit			Bud		
		Mean shedding force [N]	Mean shedding time [s]	Swing period	Mean shedding force [N]	Mean shedding time [s]	Swing period
20	2.05	6.78	3.38	5	2.37	5.97	4
20	7.51	4.57	2.96	6	3.24	5.25	4
20	12.98	7.34	1.54	4	1.98	4.76	5
50	2.05	6.58	2.47	4	2.26	4.58	6
50	7.51	11.51	1.98	6	2.54	3.42	6
50	12.98	7.38	1.27	5	1.92	2.54	4
100	2.05	11.85	1.24	5	0.93	2.57	5
100	7.51	8.54	1.08	4	0.75	1.78	4
100	12.98	7.64	0.69	5	1.88	0.83	4

The table also indicates that at low frequency (2.05 Hz), increasing the vibration amplitude from 20 mm to 50 mm results in only a 0.2 N difference in fruit shedding force and a 0.11 N difference in bud shedding force, whereas increasing the amplitude from 50 mm to 100 mm causes fruit shedding force to rise from 6.58 N to 11.85 N and bud shedding force to decrease from 2.26 N to 0.93 N; at high frequency (12.98 Hz), the effect of vibration amplitude on the shedding force of both fruits and buds is negligible.

The shedding time of Camellia oleifera fruits and buds is inversely related to excitation parameters, decreasing as either vibration amplitude or frequency increases, with the rate of change in fruit vibration shedding time being lower when increasing from low frequency (2.05 Hz) to medium frequency (7.52 Hz) than when transitioning from medium frequency (7.52 Hz) to high frequency (12.98 Hz), while the opposite pattern is observed for buds, where the change rate is higher during the low-to-medium frequency increase than during the medium-to-high frequency increase.

Movement rules of Camellia oleifera fruit and bud

(a) *Fruit movement path* (b) *Locus of bud movement*

Fig. 2 - Motion state of *Camellia oleifera* fruit under forced vibration

Under the condition that Camellia oleifera fruits and buds move within the same plane, high-speed video was used to capture the approximate trajectories of fruits (Fig. 3a) and buds (Fig. 3b) under vibration excitation with a vibration amplitude of 50 mm and a frequency of 7.52 Hz. Vibrational energy is transferred to the fruits and buds through the branches, disrupting the overall system balance and causing the fruits and buds to exhibit anisotropic random and disordered mixed oscillation behavior *(Hoshyarmanesh et al., 2017; San et al., 2018)*.

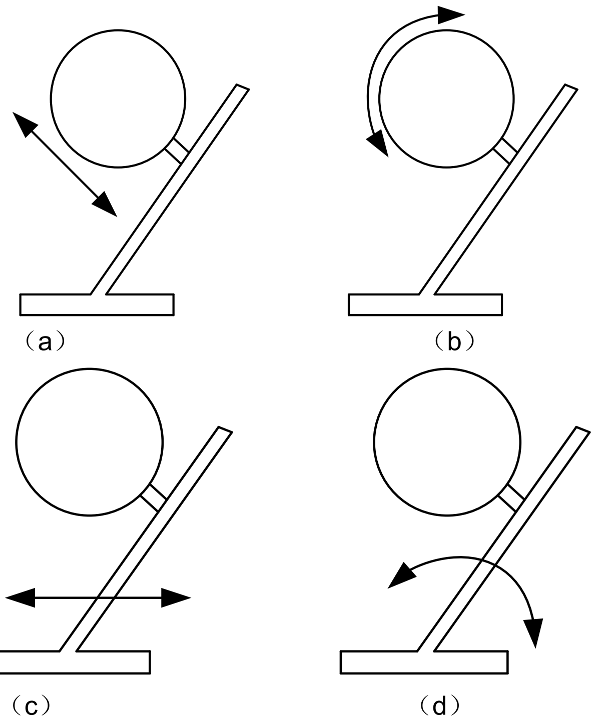


Fig. 3 - Motion decomposition

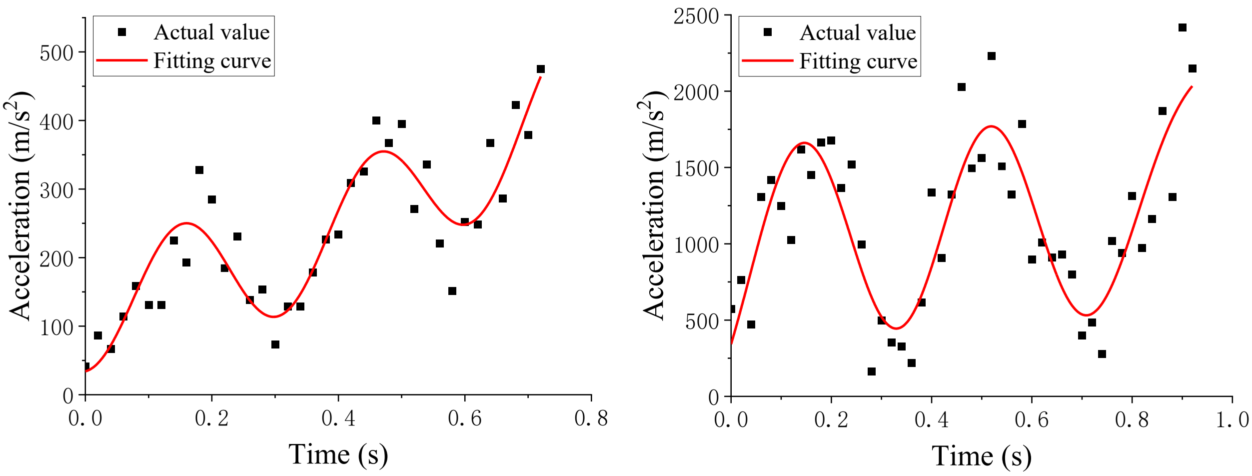
(a) Parallel stalk movement of fruit; (b) The fruit moves around the stalk; (c) The fruit and the branch move together; (d) The fruit and the branch move together around the excitation point.

Trajectories of Camellia oleifera Fruit and Buds Under 7.52 Hz Excitation (Fig. 2). Under 7.52 Hz excitation, Camellia oleifera fruits and buds exhibit dynamic oscillatory behavior: they first accelerate and swing in the direction of the applied force, then rapidly reverse direction. The entire branch-fruit and branch-bud system undergoes periodic oscillations around the excitation origin. Notably, the fruit and its supporting branch show significant positional displacement, characterized by wobbling of the fruit and torsional movement of the branch. Observation points on the structures demonstrate altered relative positions, with marked fruits displaying obvious deflection. This complex motion can be attributed to the combined behaviors illustrated in Figure 3, consistent with similar findings in prior studies *(Cao et al., 2023; Hoshyarmanesh et al., 2017; San et al., 2018; Wang et al., 2024)*.

As shown in Figure 4, the movement trajectories of fruits and buds do not reciprocate along a straight line within the same period, indicating relative motion (e.g., swinging or twisting) between fruits and branches during vibration. Under identical vibration conditions, fruits exhibit significantly greater motion responses (i.e., displacement) than buds. The movement of fruits and buds is also influenced by neighboring fruits and branches in an unpredictable manner, leading to frequent changes in their trajectories due to potential collisions. Quantitative analysis of these trajectories represents a promising direction for future research.

Motion curve fitting

When the camellia fruit and flower bud acquire sufficient inertial force, that is, when the critical value of the binding force between the fruit stem and the branch is exceeded, the camellia fruit or flower bud will fall off. Through the analysis of the movement images and data of the target camellia fruit and flower bud captured by the high-speed camera, the sample will be taken every 0.02 s, as shown in Figure 4 of the acceleration and time relative to the origin point.



(a) fruit (b) bud

Fig. 4 - Vibration shedding process

From the beginning of vibration to the shedding acceleration, *Camellia oleifera* fruit experienced three stages: 0 to 0.3 s, 0.3 to 0.58 s and 0.58 to 0.72 s. The first stage period of *Camellia oleifera* fruit was 0.3 s, and the peak acceleration occurred at 0.18 s (328.24 m/s²). The period of the second stage is 0.28 s, and the peak acceleration occurs at 0.46 s and is 400.18 m/s². The fruit of *Camellia oleifera* fell off before reaching the complete cycle in the third stage. The vibration shedding time was 0.72 s and the shedding acceleration was 475.38 m/s². Fourier fitting was performed on the acceleration of *Camellia oleifera* fruit. The R2 of the fitting curve was 0.83996, and the equation of the fitting curve was as follows:

$$a_g = 208.52 + 1612.57\sin(0.59t) - 85.14\cos(0.002t) - 383.53\sin(1.87t) - 89.25\cos(20.52t) \tag{5}$$

There were 3 stages from the initial vibration to the shedding acceleration: 0 to 0.36 s, 0.36 to 0.74 s and 0.74 to 0.92 s. In the first stage, the movement period was 0.36 s, and the peak acceleration occurred at 0.2 s (1676.63 m/s²). The period of the second stage is 0.38 s, and the peak acceleration occurs at 0.52 s, which is 2232.17 m/s². The buds of *Camellia oleifera* fell off before reaching the complete cycle in the third stage.

The vibration shedding time was 0.92 s, and the shedding acceleration was 2147.4 m/s^2. Fourier fitting was performed on the acceleration of *Camellia oleifera* bud. The R2 of the fitting curve was 0.73718, and the equation of the fitting curve was as follows:

$$a_h = -780.29 + 39212.57\sin(0.11t) + 1375.24\cos(3.45t) + 471.89\sin(14.61t) - 252.91\cos(18.72t) \quad (6)$$

CONCLUSIONS

In this paper, the motion of *Camellia oleifera* fruit and bud was observed by image acquisition technology, and the motion behavior of *Camellia oleifera* fruit and bud under different vibration parameters was analyzed in detail. By using mathematical model to study the characteristics of *Camellia oleifera* branches, and using high-speed photography technology to measure and analyze the dynamic characteristics of *Camellia oleifera* fruits and buds, the following conclusions are drawn:

- The maximum relative error between the theoretical value and the actual value of the output acceleration of the exciter is 1.84%; The fruit shedding force of *Camellia oleifera* ranged from 4.57 N to 11.85 N, and the bud shedding force ranged from 0.68 to 3.24 N.
- Under high frequency (12.98 Hz) vibration, the change of vibration amplitude has no obvious effect on the shedding force of fruit and bud. The shedding time of *Camellia oleifera* fruit and bud decreased with the increase of vibration amplitude or excitation frequency.
- The vibrational energy is transferred to the fruit and bud through the branches, the balance of the whole system is broken, and the fruit and bud show anisotropic random and disorderly chaotic oscillation behavior;
- Using the collected data for fitting analysis, the Fourier fitting curve and your sum function of the motion acceleration of *Camellia oleifera* fruit and the bud were obtained, with R2 of 0.83996 and 0.73718, respectively.

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