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Article

Modal Variability of *Ginkgo* Seed–Stem System Based on Model Updating

Jie Zhou [1,2,3], Linyun Xu [2,*], Hongping Zhou [2], Rongshan Zhang [3], Zhicheng Jia [2], Fubao Zhang [1], Yue Zhang [1], Juan Chen [1] and Cheng Zhang [1]

[1] School of Mechanical Engineering, Nantong University, Nantong 226019, China; jiezhou@ntu.edu.cn (J.Z.); zhang.fb@ntu.edu.cn (F.Z.); yuezhang@ntu.edu.cn (Y.Z.); chenjuanwhy@outlook.com (J.C.); zhangcheng@ntu.edu.cn (C.Z.)
[2] School of Mechanical and Electronic Engineering, Nanjing Forestry University, Nanjing 210037, China; hpzhou@njfu.edu.cn (H.Z.); jzcnfu@njfu.edu.cn (Z.J.)
[3] Jiangsu Linhai Power Machinery Group Co., Ltd., Taizhou 225300, China; zhrshtz@sina.com
* Correspondence: lyxu@njfu.edu.cn

Abstract: An accurate simulation model is crucial for the analysis of the correct modal information of the *ginkgo* seed–stem system (*ginkgo* subsystem). This underpins the provision of technical rationale for efficient and low-damage precision vibrational harvesting operations in *ginkgo* cultivation. In this study, based on the modal parameters of the *ginkgo* subsystem, a finite element model updating method is proposed to correct the elastic modulus of the stem with the natural frequency of the first bending mode. The large difference in the modal results calculated before and after model updating reveals that model updating is a critical step in the finite element analysis of crop subsystems. Then, an uncertainty parameter modeling method is proposed to investigate the modal variability of the *ginkgo* subsystem by finite element analysis. The results show that the stem length is a key parameter affecting the variability of natural frequencies, and the seed weight is a minor parameter. The variability of the *ginkgo* seed's gravity center offset has a negligible effect on the natural frequencies of the system. The first natural frequency of the *ginkgo* subsystem can be utilized for vibrational harvesting. In addition, since the difference between the upper and lower limits of the first natural frequency of the *ginkgo* subsystem does not exceed 1 Hz, a specific excitation frequency can cause most *ginkgo* subsystems to resonate. This result facilitates the determination of precise excitation frequencies for efficient and low-damage *ginkgo* vibrational harvesting, ensuring both economic and ecological benefits in the management of *ginkgo* plantations.

Keywords: *ginkgo* subsystem; precise excitation frequencies; model updating; modal variability; vibration harvesting

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1. Introduction

Ginkgo is one of the most valuable medicinal tree species, and *ginkgo* seed has high edible and medicinal values due to its richness in protein, carbohydrates, and bioactive compounds [1,2]. China has more than 90% of the world's *ginkgo* resources, and the cultivation scale is increasing year by year [3]. However, *ginkgo* seeds are still mainly harvested by hand, and the labor shortage has led *ginkgo* planters to look for efficient mechanized harvesting methods. Vibration harvesting presents a feasible approach to lowering the cost of harvesting by providing sufficient inertial force to the *ginkgo* seeds, facilitating their detachment from the branches [4]. Vibration harvesting has been applied to harvest citrus, cherry, apple, etc. [5–9].

In order to achieve a maximum vibrational effect with minimal energy expenditure during vibrational harvesting, clearly defining the vibrational characteristics of the crop is an essential prerequisite for designing harvesting machinery and realizing precise operational execution [10]. The mode is the inherent vibration characteristic of the structural system. If the natural frequency and the modal shape of a structure in a certain susceptible frequency range are determined through modal analysis, it is possible to predict whether the structure will resonate under the excitation in this frequency range. Therefore, the studies on vibration harvesting initially focused on the modal properties of trees [11,12], but an unavoidable problem arose: due to complex topology [13], even within the same species, considerable variability is observed in the modal parameters among different individuals. Additionally, varying resonance frequencies exist within different parts of the same fruit tree, making it challenging to accurately determine the optimal harvesting frequency for these trees [9,14].

Consequently, in current practical applications, the resonance frequency of the fruit trees is often disregarded, and a method of low-frequency, high-amplitude vibrational harvesting is adopted. This crude harvesting method inevitably leads to significant damage to the fruit trees, impacting their yield in subsequent years. Moreover, the higher energy consumption associated with this method results in increased carbon emissions, adversely affecting the ecology and management of plantations. However, for the basic subsystems of the same tree species, the topology of the stem–fruit system varies less. This suggests that they may share similar modal parameters [15,16], indicating that certain vibrational frequencies might induce a significant resonant response in the fruit with only minimal vibration of the tree body, thus facilitating fruit drop. Such an approach could optimize harvesting efficiency while minimizing damage to fruit trees.

Due to the small size of crop subsystems, applying the experimental modal testing methods commonly used in engineering becomes challenging for acquiring detailed modal information of the structure at each order. As an alternative to experimental modal analysis, finite element numerical simulation is an effective tool for crop subsystem modal analysis [17], and it allows to obtain the natural frequencies and corresponding modal shapes at each order relatively easily [18]. For computational modal analysis, constructing an appropriate simulation model is essential as a prerequisite for achieving accurate finite element simulation outcomes for the crop subsystem. However, the crop to harvest is not an engineered structure but a bio-system with material anisotropy and viscoelasticity [19,20].

In prior finite element analysis research, the material composition of the crop is frequently simplified to that of a linear elastic material [18,21,22]. Especially, the corresponding elastic modulus is obtained after tensile or bending tests on the stems in the stem–fruit system and used directly in numerical simulations. In the simulation process of determining the material properties of the system structure, there are two under-appreciated but not negligible questions: (1) For the simplified material in the simulation, if only one-sided elastic modulus measurements are taken and used directly in the simulation, how big is the difference between the obtained system dynamic properties and the real ones? (2) For the elastic modulus of the stem test, are the obtained test values accurate due to the small size of the structure? The small shape of subsystems makes it impossible to perform tests according to the standards in the material industry. The error caused by these two problems to the modal analysis results is incalculable. Therefore, to make the finite element model (FEM) consistent with the real vibration characteristics of the crop, it is important to update the FEM accurately.

Being a gymnosperm, the target for harvesting in *ginkgo* is essentially its seed, making this subsystem its fundamental subsystem. Owing to the biological system's physical variability, the modal parameters vary across different individual *ginkgo* subsystems. Therefore, the difference and its influence on the harvester's design need to be determined. For the natural variability of crop systems, the uncertainty parameter modeling can take the actual measured values as a reference in the finite element modeling. At the same time, the physical parameters that differ between systems (e.g., weight, physical dimensions, and elastic modulus) are set as stochastic parameters, following which the distribution modal parameters of crop systems can be obtained. The influence of these stochastic parameters on the modal analysis results has not been investigated by existing studies. Determining the influence of stochastic parameters on system mode is the prerequisite for understanding crop modal variability. The response surface method is a statistical method for solving multivariate problems, and it is an effective tool for analyzing the effect of different input conditions on the target response value [23–25]. With the response surface method, the effect of each variable parameter on the modal parameters can be investigated in the simulation of the *ginkgo* subsystems.

This study aims to provide an updating method for the *ginkgo* subsystem FEM and to investigate the error caused by an uncorrected model. In this way, this study reveals the importance of model updating and provides a reference for future model updating methods for crop subsystem numerical simulation. Simultaneously, leveraging the updated model, a methodology for uncertainty parameter modeling is introduced to study the modal variability within the *ginkgo* subsystem. These findings are expected to offer novel technical insights for the precise vibrational harvesting of *ginkgo*, contributing to both ecological and economic management of *ginkgo* plantations.

2. Material and Methods

2.1. Raw Material and Sample Preparation

The subsystems of *ginkgo* trees growing at the *ginkgo* plantation affiliated with Nanjing Forestry University (Nanjing, China) were investigated in this study. *Ginkgo* subsystems, harvested during the maturation phase of *ginkgo* seeds, served as experimental samples. They consist of a branch, stem, and seed (see Figure 1). To ensure the generalizability of test results, samples were randomly chosen from various *ginkgo* trees and different tree sections. Immediate utilization of the collected samples in experiments was prioritized to prevent errors in test outcomes due to water evaporation.

Figure 1. The structure of the *ginkgo* subsystem.

2.2. Model Updating Process

Model updating describes a class of methods that use experimental data to correct the uncertainty parameters in numerical models. The main objective is to improve the correlation of the test model, i.e., the ability of the model to correctly represent the target structure dynamics. The existing model updating methods in engineering can be roughly classified according to the experimental data types used to quantify the correctness of the model. The common choices include modal parameter estimates (natural frequency and modal shape) and measured frequency response functions (FRFs) [26]. The experimental data are used to adjust the model parameters until the error between the experimental data and the model output is minimized [27].

It is impractical to test the FRFs of the *ginkgo* subsystem with a small structure and large flexibility. However, its specific modal parameters can be measured. The subsystem can be regarded as a single pendulum structure, and its first natural frequency is the swing frequency in its free vibration state. In industry, the identification or updating of the elastic modulus of materials is often based on the natural frequency and elastic modulus correlation of the engineering structure, such as the first bending mode natural frequency or the torsional modulus natural frequency [19,28] of the bridge structure. This method can also be adapted to the *ginkgo* subsystem, enabling the correction of the elastic modulus in the model by utilizing the correlation between the system's first natural frequency and the stem's elastic modulus. The first natural frequency of the subsystem can be derived from its free vibration decay signal [29,30].

In this study, the fundamental approach for updating the FEM of the *ginkgo* subsystem hinges on using the system's first natural frequency as the reference point for model modifications. Initially, the elastic modulus of the *ginkgo* stem, derived from physical tensile testing, was directly applied in the modal analysis of the subsystem following 3D reconstruction. This process was undertaken to determine the uncorrected first natural frequency. Concurrently, the actual first natural frequency was ascertained through a free vibration test of the subsystem. Following this, the simulated outcomes of the uncorrected model were compared with the actual results, leading to subsequent corrections in the model. Then, to obtain the correlation between the first natural frequency of the subsystem and the stem's elastic modulus, a response surface-based stochastic finite element analysis of the *ginkgo* subsystem was performed with the assistance of the ANSYS Workbench 19.0 software (ANSYS, Scotts Valley, CA, USA). The stem's elastic modulus in the model was set as the input stochastic parameter, and the first natural frequency of the subsystem was set as the response output parameter. Central composite design (CCD) was taken as the sample point selection technique to fit the response surface, and the response surface type was a fully quadratic polynomial standard response surface. Once the relationship between the stem's elastic modulus and the first natural frequency was established, the updated value of the stem's elastic modulus in the modal analysis was determined. This update was based on the actual first natural frequency derived from the free vibration test of the subsystem conducted initially. Finally, a subsequent modal analysis of the *ginkgo* subsystem was carried out to acquire the updated modal parameters of the system. The overall process is shown in Figure 2.

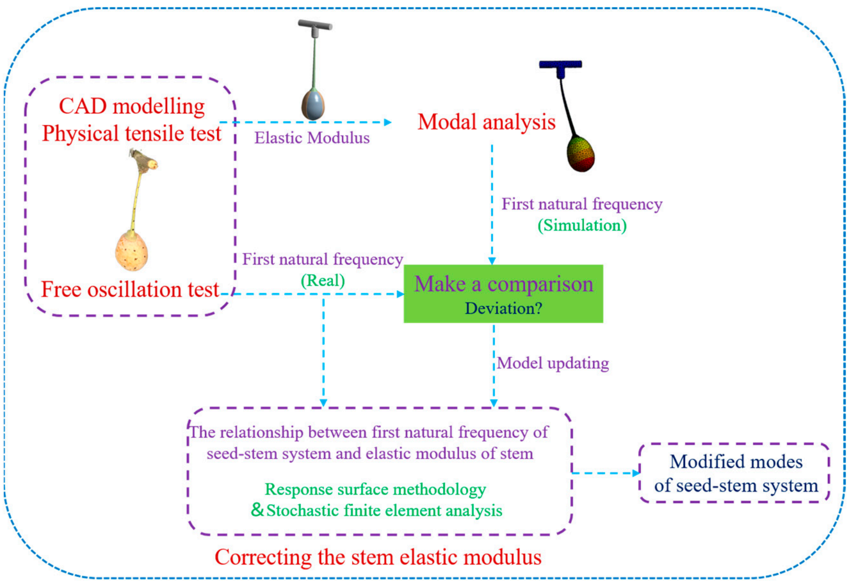

Figure 2. The process of model updating.

For the purpose of model updating, it is not essential to measure the stem's elastic modulus directly, since the correction of the elastic modulus can be acquired through the response surface-based stochastic finite element analysis. In this study, the stem's elastic modulus was measured to compare the difference between the calculation results before and after model updating, thus revealing the importance of model updating.

2.2.1. Physical Tensile Test

In the proposed finite element simulation, it is considered that the *ginkgo* subsystem is linearly elastic, so one elastic constant is sufficient for each substructure. During the actual process of vibration harvesting, the vibrational deformation of the subsystem is primarily manifested through the deformation of the stem. As a further simplification, the elastic modulus of the branches and seeds in the system model can be set large enough for better rigidity. Since the stem of *ginkgo* is too thin and soft, only a small force along the cross-sectional of the stem can cause a large deformation of the stem. In this case, the bending test used in previous studies to measure the stem elastic modulus of coffee or grapes cannot be applied to the stem of *ginkgo* because the force sensor sensitivity does not meet the requirements of the test. By contrast, a tensile test can be performed on the stem to obtain its elastic modulus.

The elastic modulus of 20 *ginkgo* stem samples was measured, and the result is shown in Figure 3. The tensile test equipment for the stem consists of a digital force gauge (Model HP-50, Edberg Instrument, Zhejiang, China), a screw lift stand, two high-speed cameras (M310; VEO410, Vision Research, Birmingham, AL, USA), and clamps. The upper and lower ends of the *ginkgo* stems were restrained on the clamp. At the same time, the stems were stretched along the axis of the stems using a screw lift bracket, and the tensile load was displayed on a tensimeter in real-time. To avoid the error caused by the relative slippage between the clamp and the stem when the stem was stretched and deformed, the distance between the two markers on the *ginkgo* stem instead of the distance between the clamps was used as the initial length L in the calculation of the strain. One high-speed camera captured the stem being stretched to obtain the elongation ΔL in real-time, and the other high-speed camera captured the tension F displayed on the tensiometer. The two high-speed cameras shot simultaneously to obtain the real-time change relationship between the elongation ΔL and the tensile force F to calculate the elastic modulus. The stem of *ginkgo* is structurally similar to a variable-section beam. For the convenience of calculation, the marked section of the stem in Figure 3 was approximated as an equal-section beam, and the section area at the two marked points was averaged as the section area A in the calculation.

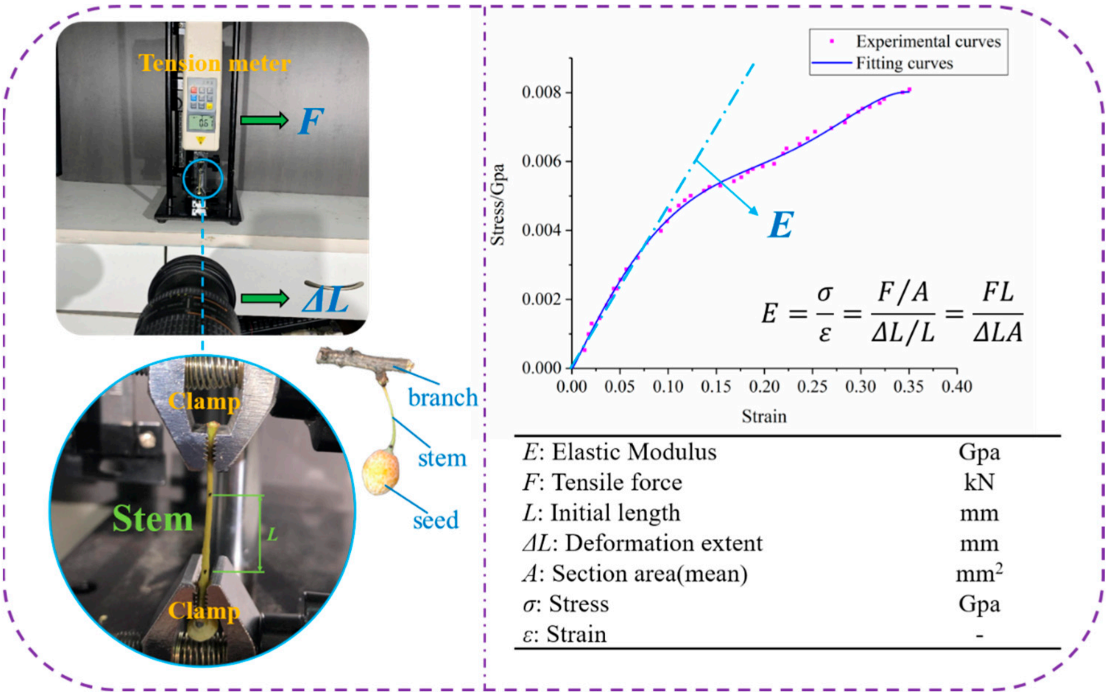

Figure 3. The physical tensile testing set-up and the test result.

The stress–strain curve of the stem was obtained by fitting the relationship between the stress and strain of the *ginkgo* stem obtained from experiments (Figure 3). It can be seen that the stem exhibited elastic deformation during the initial phase of stretching. When the stress continued to increase, the elastic deformation was transformed into plastic deformation. During vibration harvesting, the stress on the *ginkgo*'s stem is not sufficient to cause plastic deformation. Therefore, only the mechanical properties of the stem at the stage of elastic deformation need to be considered in this study. The slope of the stress–strain curve at the stage of elastic deformation of the stem is the elastic modulus of stem E. The measured average elastic modulus was 0.075 GPa, with a standard deviation of 0.003 GPa. During the test period, the difference in the elastic modulus between different *ginkgo* stems was not significant.

2.2.2. Free Oscillation Test

In the free vibration test of the *ginkgo* subsystem (Figure 4), the branch movement within the system was restricted. An initial displacement was then imparted to the seed, allowing it to swing freely. The surface of the *ginkgo* seeds was marked with tracking points, and their 3D movement trajectory was monitored using two high-speed cameras to record the displacement decay curve. The first natural frequency of the *ginkgo* subsystem was determined through a fast Fourier transform analysis of this displacement decay curve. For this study, the image acquisition setup included two high-speed cameras, a computer, TEMA motion 3D 3.0 software (provided by Image Systems AB, Ostergotlands Lan, Sweden), and relevant data analysis and processing software.

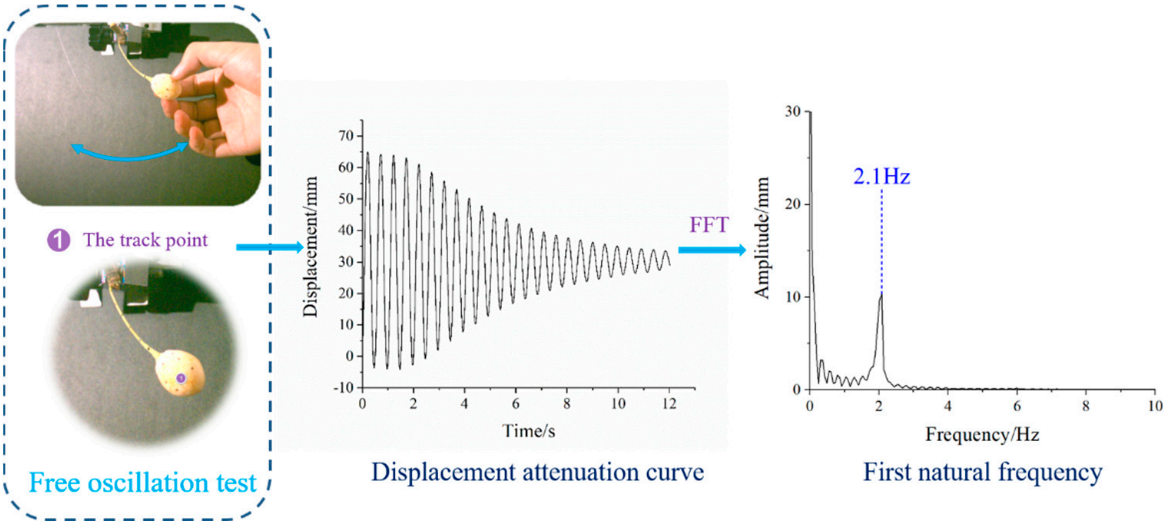

Figure 4. The free oscillation testing set–up and the test result.

A total of 50 samples of the *ginkgo* subsystem were randomly selected and tested for free vibration, and the average first natural frequency of the subsystem was obtained as 1.93 Hz with a standard deviation of 0.36 Hz. It can be seen that the first natural frequencies of different samples in the subsystem were similar. One of the test samples was selected for 3D reconstruction, and an initial finite element modal analysis was performed. With the first natural frequency of 2.1 Hz, the displacement decay curve obtained in the free vibration test of this sample is shown in Figure 4, and the model parameters after 3D reconstruction are shown in Section 2.2.3.

2.2.3. Establishment of the Simulation Model

The procedure of establishing the *ginkgo* subsystem FEM before correction is shown in Figure 5. The solid model was constructed with Solidworks 14.0 (Dassault Systemes, Paris, France) based on the shape-structure parameters of the selected subsystem. Then, the solid model was imported into the ANSYS Workbench 19.0 software to divide the mesh and determine the model constraints and material parameters for the subsequent modal analysis. In practical scenarios, the *ginkgo* seed is not perfectly centrosymmetric, and its center of gravity does not precisely align with the geometric centroid of the seed. Therefore, the seed in the system model is divided into two parts with different densities, so that the gravity center deviates from the centroid. In the initial setting of the model, to keep the average density of the seed consistent with the actual situation, the gravity center offset of the seed is set to 2.56 mm, i.e., 11.8% of the seed transverse diameter.

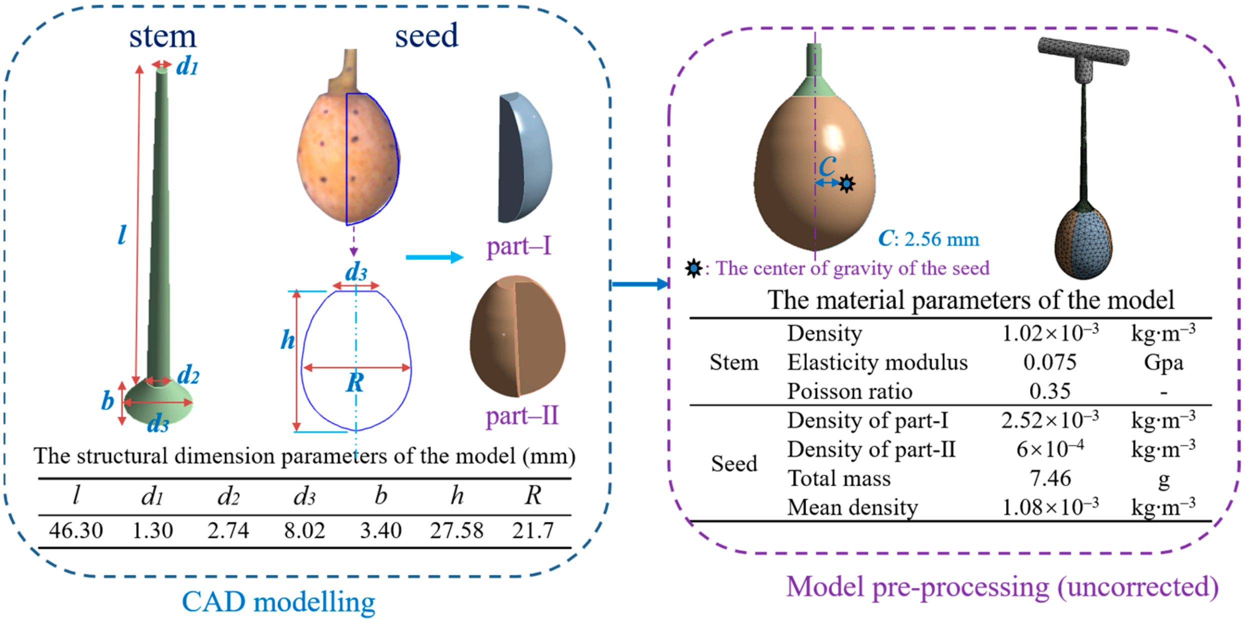

Figure 5. Establishment of the finite element model of the *ginkgo* subsystem.

The dynamic deformation of the *ginkgo* subsystem under forced vibration is predominantly indicated by the deformation of the stems. Consequently, in the modal analysis, the elastic moduli of the branch and the seed within the model were assigned high values, and the displacement of the branch was constrained to reflect this behavior. Then, the material parameters that need to be determined in the model were the stem density, the elastic modulus, the Poisson's ratio, and the average density of the seed. By weighing 100 *ginkgo* subsystem samples and measuring the volume based on the drainage method, the averaged stem density and seed density were obtained as the corresponding model parameters. The initial reference value for the stem's elastic modulus is the test value obtained in the physical tensile test. In simulations, the Poisson's ratio of the material is often set to empirical values. Poisson's ratio, a constant characterizing the relationship between transverse and axial deformation in elastic materials, generally has a minimal impact on the results of modal analysis. In previous simulation studies, the Poisson's ratio for the stem is commonly set within the range of 0.3 to 0.4 [18,19], so the initial value of the Poisson's ratio was set to 0.35 in this study.

2.3. Modal Variability Identification

For the natural variability of the physical properties of the *ginkgo* subsystem, uncertainty parameter modeling was used by this study to investigate the modal variability, and the setting of each parameter is shown in Figure 6. Since the experimental values of the elastic modulus of different stems are almost the same during the test period, under the premise that the branches and seeds of the *ginkgo* subsystem are approximated as rigid bodies and the branch displacements are constrained, the structure parameters and the seed weight of the stem affect the modal differences between different *ginkgo* subsystems. The variability of the structure parameters of the stem is mainly reflected by the stem length, so the stem length was set as a stochastic parameter in the developed subsystem model, and it ranged from 40–55 mm. The variability in seed weight randomness can be introduced by designating the model density as a stochastic parameter without altering its overall dimensions. It's noteworthy that the structure of the seed model in this study comprises two parts, leading to the incorporation of two stochastic density parameters. This indicates that only the numerical distributions of the stem length and seed weight need to be sampled and measured as the range to set these two stochastic parameters in the model. Then, the natural frequency distribution and vibration mode of the subsystem were obtained by the stochastic finite element modal analysis after model updating. The ranges of the seed weight and stem length shown in Figure 6 were obtained by measuring 300 stochastic samples. To understand the effect of model updating on the finite element analysis results and determine whether the effect of the Poisson's ratio is small enough on the results, the elastic modulus and Poisson's ratio of the stem were also set as stochastic parameters in the finite element analysis. The stem's elastic modulus was set between the tested and corrected values. The Poisson's ratio of the stem was limited to a value between 0.3 and 0.4, which is commonly used by previous studies. The output parameters of stochastic finite element analysis are the natural frequency and modal shape of the subsystem. As the stochastic parameters to be defined encompass structural parameters of the model, such as stem length, the stochastic finite element analysis of the subsystem was executed through the collaborative simulation of Solidworks 14.0 and ANSYS Workbench 19.0.

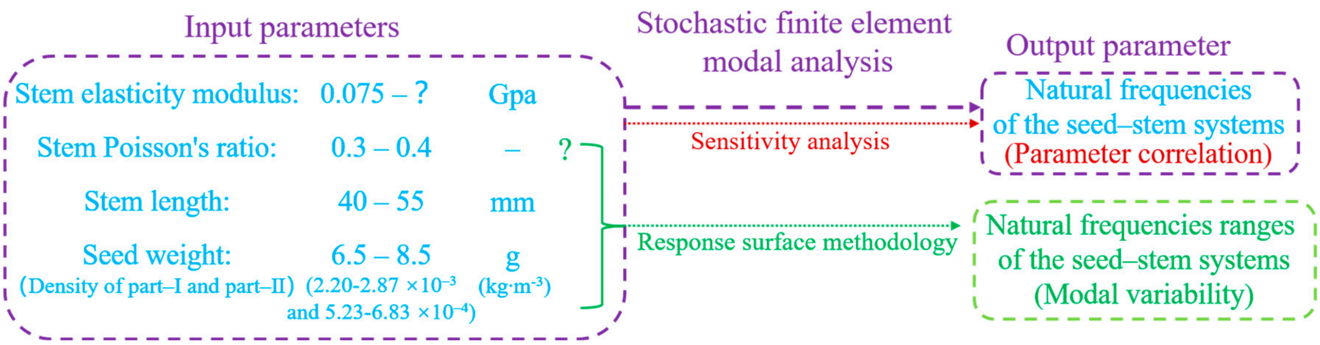

Figure 6. The process of modal variability analysis of the *ginkgo* subsystem.

After the stochastic finite element analysis was completed, the correlation between these stochastic input parameters and the finite element analysis output parameters was investigated by sensitivity analysis to measure the contribution of the input parameter uncertainty to the output natural frequency uncertainty. Finally, the subsystem's modal variability was determined through response surface analysis to obtain the distribution of the natural frequencies of the *ginkgo* subsystem. In the response surface analysis, seed weight and stem length were used as input parameters (whether the Poisson's ratio of the stem is used as one of the input parameters depends on the sensitivity analysis results).

3. Results and Discussion

For the modeled *ginkgo* subsystem, the modal analysis results before and after model updating are shown in Figure 7. Upon establishing the curve relationship between the elastic modulus and the first natural frequency of the stem, the updated elastic modulus of the stem was determined to be 0.3 GPa, relying on the actual first natural frequency obtained from the free vibration test of the subsystem. The elastic modulus of the stem before model updating was set to 0.075 GPa, and that after the correction was four times that before the correction. It can be seen that the difference in the setting value of the stem elastic modulus before and after model updating is quite large, which reflects the necessity of model updating. Since the model updating was based on the modification of the stem elastic modulus and did not change the structure and shape of the model, the modal shape of the subsystem before and after model updating was the same. The first and second modal shapes of the subsystem appeared as the bending of the stems in two mutually perpendicular directions, resulting in the same natural frequency of the two orders of modes. The shape of the third mode was a twist of the stems. The fourth modal shape similarly manifested stem bending, although the bending pattern differed from that of the first and second modes. Its bending pattern resembled the third bending mode of a cantilever beam. In contrast, the first and second modal stems exhibited bending patterns akin to the first bending mode of a cantilever beam.

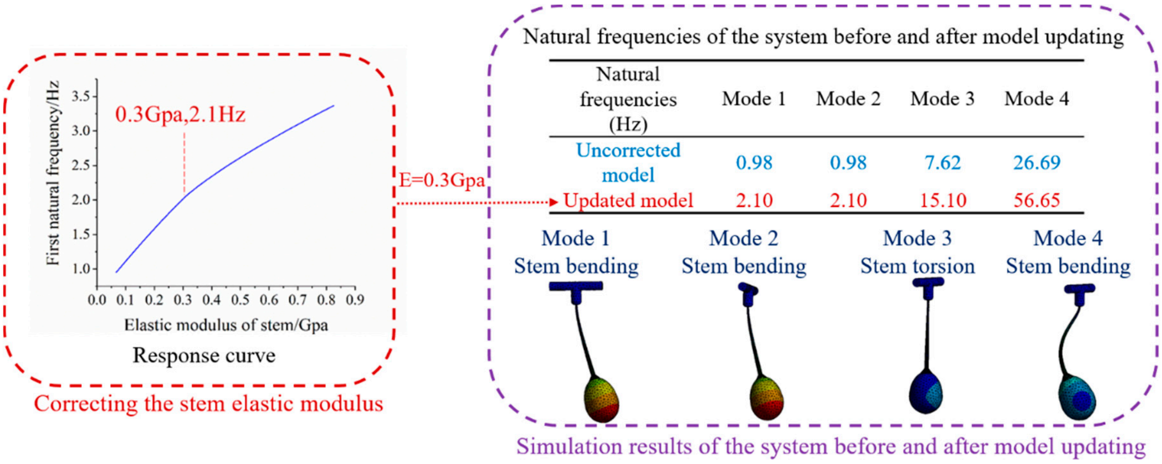

Figure 7. Modal analysis results of the subsystem before and after model updating.

The modal results before and after model updating mainly differed in the natural frequency. Taking the first natural frequency as an example, the simulated value before model updating was 0.98 Hz, and the corrected value was 2.10 Hz, which is 2.14 times that before the correction. This indicated that for any kind of crop, a modal simulation that ignores the model updating step inevitably produces incorrect modal information, and the deviation from the actual dynamic properties of the crop cannot be calculated.

The modal shapes of the first and second modes of the subsystem are perpendicular to each other, but they have the same shape and the same natural frequency. Thus, the model updating of this study actually corrects the first- and second-order natural frequency of the *ginkgo* subsystem. However, the updated stem's elastic modulus based on the first natural frequency cannot guarantee the accuracy of higher-order natural frequency simulations, i.e., the updated stem's elastic modulus may be different for different orders of modes. In this instance, it's important to note that the authenticity of the third and fourth natural frequencies of the *ginkgo* subsystem, obtained after model updating in this study, cannot be guaranteed as they have not been experimentally verified. In fact, due to the small system structure, the third and fourth natural frequencies of the *ginkgo* subsystem cannot be obtained by the experimental modal test method commonly used in engineering. Nevertheless, for the third mode of the subsystem, its modal shape is manifested as the torsion of the stem. At the same time, in the actual vibration harvesting process, it is difficult to excite the resonant torsion of the subsystem. Therefore, the third mode has no practical value for study. The vibration model of the fourth modal is expressed as the second-order bending of the stems, and it can be theoretically used in resonance-based vibration harvesting techniques. However, the fourth natural frequency of the *ginkgo* subsystem is quite large both before and after model updating. In practical vibration harvesting, the aim is often to achieve efficient harvesting at low frequencies [31,32]. This is because high vibration frequencies are difficult to achieve in harvester design and can significantly affect harvester lifetime [33,34]. Therefore, the *ginkgo* subsystem only generates a resonant response near the first natural frequency within the range of vibration frequencies that can be achieved by the harvester.

Notably, the first natural frequency of the *ginkgo* subsystem can be obtained from the free vibration test. Nevertheless, it makes sense to modify the simulation model to calculate the already known modal parameters. On one hand, due to natural variability, each *ginkgo* subsystem is an individual, and its modal parameters must be different. It is impractical to test all subsystems. In finite element simulation, only the parameter variability between systems after model updating needs to be considered. Based on this, the distribution range of all individual modal parameters can be easily and quickly obtained, thus providing a technical reference for determining the appropriate excitation frequency in vibration harvesting. On the other hand, with the model updating of the *ginkgo* subsystem, the modal parameters can be obtained, and the dynamic behaviors of the *ginkgo* subsystem under excitation can be accurately simulated in the subsequent dynamics simulation. This is attributed to the fact that the modal parameters as natural vibration characteristics of the structure greatly affect the dynamic response [33].

Figure 8 shows the sensitivity analysis results for each stochastic input parameter of the output natural frequency in the finite element analysis of the *ginkgo* subsystem. It can be seen that the stem's elastic modulus has the greatest influence on the natural frequency, followed by the length, seed weight, and the stem's Poisson's ratio. This result once again illustrates the need to correct the stem's elastic modulus in the modeling of the subsystem. The stem's Poisson's ratio has a small effect on the third natural frequency within the set range, and it has almost no effect on the modes of other orders. The third modes of the subsystem are not related to vibration harvesting, so the uncertainty of the stem's Poisson's ratio does not need to be considered in the investigation of the modal variability of the subsystem. Additionally, the elastic modulus of the stem is positively correlated with the natural frequency of the subsystem, and the other input parameters are negatively correlated with the natural frequency of the subsystem. This is due to the fact that, in modal analysis, the natural frequency of the structure is the square root of the ratio of the stiffness matrix to the weight matrix. The larger the stem's elastic modulus, the larger the stiffness of the structure. In addition, the stem length is negatively correlated with structural stiffness.

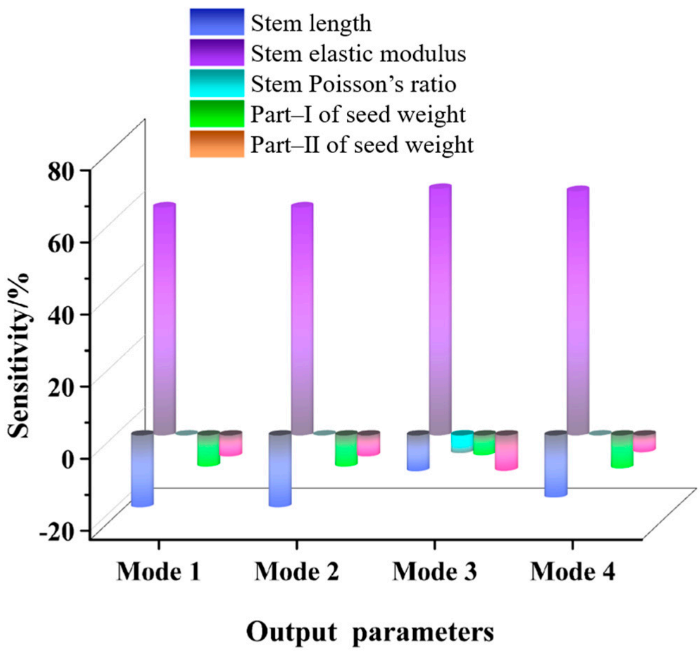

Figure 8. Sensitivity of the natural frequency of the system to stochastic input parameters.

The sensitivity analysis results indicate that the variability of the stem's elastic modulus has the greatest effect on the *ginkgo* subsystem natural frequency within the range of each parameter. However, this may not hold in real situations. In the sensitivity analysis, to illustrate the importance of updating the stem's elastic modulus, the updating range was set between the measured and corrected values, so the sensitivity value of the stem's elastic modulus is maximized. According to the tensile test results of the stem, different *ginkgo* stem individuals have a similar elastic modulus in practice. Therefore, the stem's elastic modulus can be considered as a constant when exploring the modal variability of the *ginkgo* subsystem after the stem's elastic modulus is corrected.

For the corrected *ginkgo* subsystem model, when the stem's elastic modulus and Poisson's ratio are considered as constant, the uncertain parameters causing modal variability are the stem length and seed weight. The response surface cloud plots of Figure 9a,b show the relationship between the stem length, Part-I of seed weight, Part-II of seed weight, and the first natural frequency of the subsystem. Based on the distribution of the seed weight and the stem length measured by extensive sampling, the first natural frequency of the *ginkgo* subsystem was 1.53–2.51 Hz, and the difference between the upper and lower frequency limits did not exceed 1 Hz. According to the theory of vibration mechanics, the resonance phenomenon does not occur only at the natural frequency, and there is a resonance region near the natural frequency. That is, resonance may occur if the excitation frequency falls within this resonance region. Thus, during vibration harvesting, the excitation frequency around 2 Hz can cause most *ginkgo* seed–stem individuals to undergo main resonance. This conclusion was consistent with the phenomenon of motion response of *ginkgo* subsystem under forced vibration [35]. The computational simulation results of the crop subsystem based on a simplified model of the double-physical pendulum [36,37] indicate that the resonance of the subsystem occurs at twice the first natural frequency in the presence of the vertical component of the excitation. When the excitation frequency is around twice the first natural frequency, the system has a wider resonance frequency region and a larger resonance intensity, and the resonances at twice the natural frequency are subharmonic. According to this, the most suitable excitation condition for *ginkgo* harvesting is an excitation frequency of 4 Hz and a vertical component of the excitation. Under this condition, the specific excitation frequency can cause most *ginkgo* subsystem individuals to resonate, regardless of the main or sub-harmonic resonance of the subsystem during harvesting. This implies that at these frequencies, only a small amplitude of excitation is required to cause a minor swaying of the tree's body, which can induce a significant vibrational response in the seed, leading to seed drop. In other words, based on these two frequencies, the precise vibrational harvesting of *ginkgo* can be achieved. This approach not only ensures high-efficiency harvesting but also minimizes damage to the fruit trees. Consequently, it can ensure both economic and ecological benefits in the harvesting operations of *ginkgo* plantations.

The seed in the *ginkgo* seed–stem model is divided into two parts, i.e., Part-I and Part-II. In obtaining the first natural frequency range of the *ginkgo* subsystem, the variation of the seed weight values was acquired by varying the initial value of the seed weight of the two parts in equal proportion. In the study of the modal variability, the gravity center of the seed remained constant when the weight of the seed changed, and the gravity center offset was always 11.8% of the seed transverse diameter. For a real *ginkgo* seed, due to the natural variability of the bio-system, its gravity center is not determined. In the model constructed in this study, the gravity center offset is always kept at a constant value. That is, the variability of the gravitational center offset was not considered when studying the subsystem's modal variability. Then, a *ginkgo* subsystem with a stem length of 46.3 mm and a seed weight of 7.46 g was taken to investigate whether neglecting the variability of the gravity center offset of a seed introduces a large bias to the modal variability results. Figure 10 illustrates the influence of the *ginkgo* seed gravity center offset on the first natural frequency. It can be seen that the gravitational center offset of the seed changed with the adjustment of the weight of the two parts of the seed, but the total seed weight was always constant (7.46 g). The variation of the first natural frequency of the *ginkgo* monoculture system ranged from 2.09–2.11 Hz when the gravity deviation ratio of the *ginkgo* seed was between 8% and 26%. The result indicated that the influence of the gravity center offset on the modal natural frequency was negligible. Therefore, the studies of subsystem modal variability do not need to consider the variability of gravity center offset. Nevertheless, although the seed gravity center offset does not affect the first natural frequency, it may affect the resonance amplitude of the subsystem. This problem is worth further investigation in subsequent dynamic simulations.

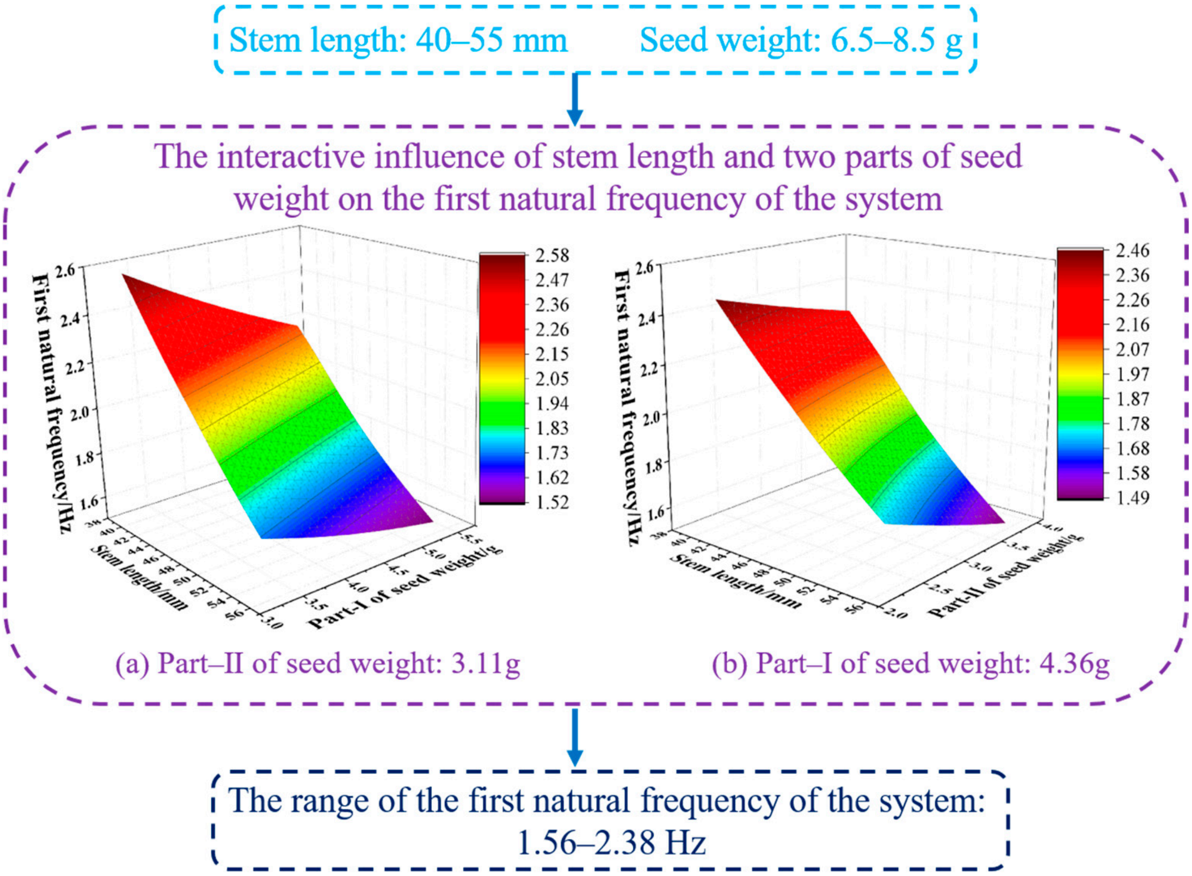

Figure 9. The modal variation range of the *ginkgo* subsystem.

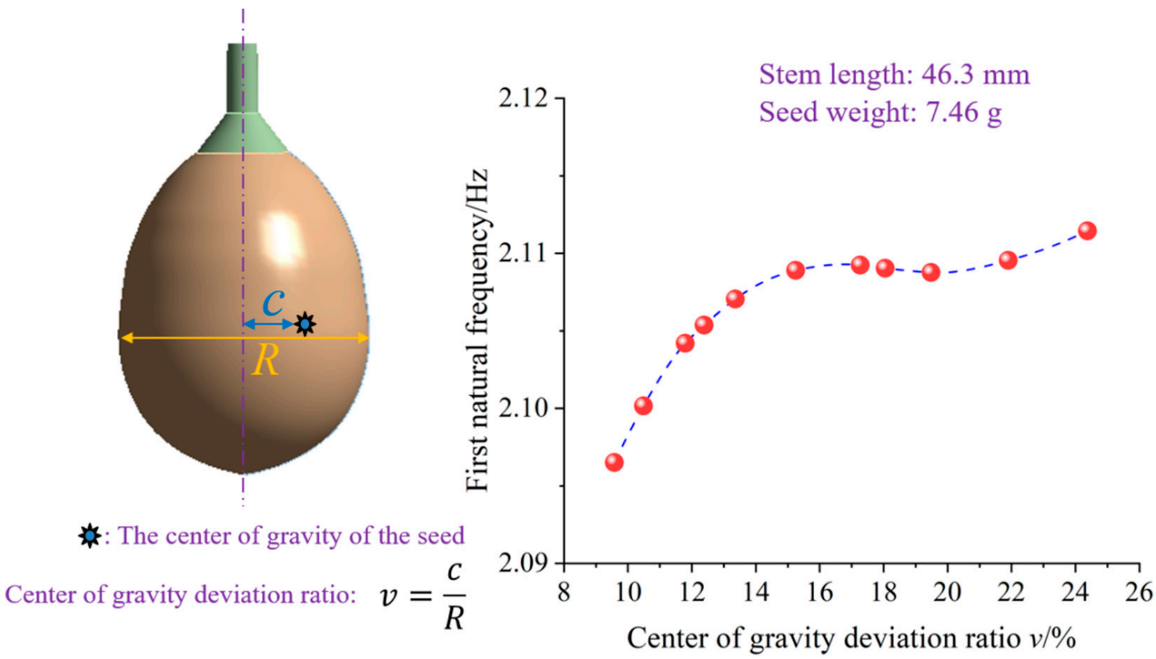

Figure 10. The influence of the gravity offset on the first natural frequency of the *ginkgo* subsystem.

4. Conclusions

This paper proposes a FEM updating method based on the modal parameters of a *ginkgo* subsystem. First, the simulated natural frequency before and after model updating was compared, and the value was nearly doubled. Such a large difference indicates that model updating is indispensable, and it is a critical step in the finite element analysis of the crop subsystem. Then, an uncertainty parameter modeling method was proposed for stochastic finite element analysis of the *ginkgo* subsystem to investigate its modal variability. The results show that stem length is a key parameter affecting natural frequency variability, and seed weight is a minor parameter. At the same time, the variability of the seed's gravity center offset has a negligible effect on the natural frequency. In addition, the first natural frequency of the *ginkgo* subsystem can be used for vibration harvesting of *ginkgo*. As the difference between the upper and lower limits of the first natural frequency of the *ginkgo* subsystem does not exceed 1 Hz, the specific excitation frequency can cause most individuals to resonate. This means that at 2 Hz and 4 Hz, a small amplitude of stimulation causing only slight swaying of the tree body can induce a substantial vibrational response in the seed, leading to seed drop. These findings establish precise excitation frequencies for efficient and low-damage *ginkgo* vibrational harvesting, ensuring the concurrent preservation of economic and ecological benefits in the management and harvesting of *ginkgo* plantations. Furthermore, the research methodology presented in this paper provides a technical reference for the precise investigation of modal characteristics in the subsystems of other crops in the future.

In future studies, we will investigate the modal variability of subsystems in a wider range of crop types, with a specific focus on different crops exhibiting significant variations in stem's structure, and verify the effect of subsystem modal variability results on dynamic response through field experiments.

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References

1. Boateng, I.D.; Yang, X.M. Do non-thermal pretreatments followed by intermediate-wave infrared drying affect toxicity, allergenicity, bioactives, functional groups, and flavor components of *Ginkgo biloba* seed? A case study. *Ind. Crops Prod.* **2021**, *165*, 113421. [CrossRef]
2. Feng, L.; Sun, J.; El-Kassaby, Y.A.; Luo, D.; Guo, J.; He, X.; Zhao, G.; Tian, X.; Qiu, J.; Feng, Z.; et al. Planning *Ginkgo* biloba future fruit production areas under climate change: Application of a combinatorial modeling approach. *For. Ecol. Manag.* **2023**, *533*, 120861. [CrossRef]
3. Guo, Y.; Wang, M.; Gao, C.; Fu, F.F.; El-Kassaby, Y.A.; Wang, T.; Wang, G. Spatial prediction and delineation of *Ginkgo* biloba production areas under current and future climatic conditions. *Ind. Crops Prod.* **2021**, *166*, 113444. [CrossRef]
4. Zhou, J.; Xu, L.; Xuan, Y.; Xu, Y.; Liu, G. Shedding frequency and motion of jujube fruits in various excitation modes. *Trans. ASABE* **2020**, *63*, 881–889. [CrossRef]

5. Castro-Garcia, S.; Blanco-Roldán, G.L.; Ferguson, L.; González-Sánchez, E.J.; Gil-Ribes, J.A. Frequency response of late-season 'Valencia'orange to selective harvesting by vibration for juice industry. *Biosyst. Eng.* **2017**, *155*, 77–83. [CrossRef]
6. He, L.; Zhou, J.; Du, X.; Chen, D.; Zhang, Q.; Karkee, M. Energy efficacy analysis of a mechanical shaker in sweet cherry harvesting. *Biosyst. Eng.* **2013**, *116*, 309–315. [CrossRef]
7. He, L.; Fu, H.; Karkee, M.; Zhang, Q. Effect of fruit location on apple detachment with mechanical shaking. *Biosyst. Eng.* **2017**, *157*, 63–71. [CrossRef]
8. Maja, J.; Ehsani, R. Development of a yield monitoring system for citrus mechanical harvesting machines. *Precis. Agric.* **2010**, *11*, 475–487. [CrossRef]
9. Zhou, J.; Xu, L.; Liu, G.; Xuan, Y.; Zhou, H.; Jiang, H. Frequency response curves and dynamic characteristics of a *ginkgo* tree in different growth periods. *Trans. ASABE* **2020**, *63*, 1673–1684. [CrossRef]
10. Hoshyarmanesh, H.; Dastgerdi, H.R.; Ghodsi, M.; Khandan, R.; Zareinia, K. Numerical and experimental vibration analysis of olive tree for optimal mechanized harvesting efficiency and productivity. *Comput. Electron. Agric.* **2017**, *132*, 34–48. [CrossRef]
11. Du, X.; Chen, D.; Zhang, Q.; Scharf, P.A.; Whiting, M.D. Dynamic responses of sweet cherry trees under vibratory excitations. *Biosyst. Eng.* **2012**, *111*, 305–314. [CrossRef]
12. Velloso, N.S.; Magalhães, R.R.; Santos, F.L.; Santos, A.A. Modal properties of coffee plants via numerical simulation. *Comput. Electron. Agric.* **2020**, *175*, 105552. [CrossRef]
13. Zhou, H.; Zhang, J.; Ge, L.; Yu, X.; Wang, Y.; Zhang, C. Research on volume prediction of single tree canopy based on three-dimensional (3D) LiDAR and clustering segmentation. *Int. J. Remote Sens.* **2021**, *42*, 738–755. [CrossRef]
14. Kazama, E.; da Silva, R.; Tavares, T.; Correa, L.; Estevam, F.; Nicolau, F.; Maldonado, W. Methodology for selective coffee harvesting in management zones of yield and maturation. *Precis. Agric.* **2021**, *22*, 711–733. [CrossRef]
15. Santos, F.L.; Scinocca, F.; de Siqueira Marques, D.; Velloso, N.S.; de Melo Villar, F.M. Modal properties of macaw palm fruit-rachilla system: An approach by the stochastic finite element method (SFEM). *Comput. Electron. Agric.* **2021**, *184*, 106099. [CrossRef]
16. Tinoco, H.A.; Peña, F.M. Harmonic stress analysis on Coffea arábica L. var. Colombia fruits in order to stimulate the selective detachment: A finite element analysis. *Simulation* **2018**, *94*, 163–174. [CrossRef]
17. Bu, L.; Chen, C.; Hu, G.; Zhou, J.; Sugirbay, A.; Chen, J. Investigating the dynamic behavior of an apple branch-stem-fruit model using experimental and simulation analysis. *Comput. Electron. Agric.* **2021**, *186*, 106224. [CrossRef]
18. Tinoco, H.A.; Ocampo, D.A.; Peña, F.M.; Sanz-Uribe, J.R. Finite element modal analysis of the fruit-peduncle of Coffea arabica L. var. Colombia estimating its geometrical and mechanical properties. *Comput. Electron. Agric.* **2014**, *108*, 17–27. [CrossRef]
19. Bu, L.; Hu, G.; Chen, C.; Sugirbay, A.; Chen, J. Experimental and simulation analysis of optimum picking patterns for robotic apple harvesting. *Sci. Hortic.* **2020**, *261*, 108937. [CrossRef]
20. Yang, L.; Yang, M.; Yang, G. Modeling fractures and cracks on tree branches. *Comput. Graph.* **2019**, *80*, 63–72. [CrossRef]
21. Liu, J.; Yuan, Y.; Gao, Y.; Tang, S.; Li, Z. Virtual model of grip-and-cut picking for simulation of vibration and falling of grape clusters. *Trans. ASABE* **2019**, *62*, 603–614. [CrossRef]
22. Villibor, G.P.; Santos, F.L.; de Queiroz, D.M.; Junior, J.K.; de Carvalho Pinto, F.D. Dynamic behavior of coffee fruit-stem system using modeling of flexible bodies. *Comput. Electron. Agric.* **2019**, *166*, 105009. [CrossRef]
23. Pereira, L.M.S.; Milan, T.M.; Tapia-Blácido, D.R. Using response surface methodology (RSM) to optimize 2G bioethanol production: A review. *Biomass Bioenergy* **2021**, *151*, 106166. [CrossRef]
24. Wang, Y.; Zhang, Y.; Yang, Y.; Zhao, H.; Yang, C.; He, Y.; Wang, K.; Liu, D.; Xu, H. Discrete element modelling of citrus fruit stalks and its verification. *Biosyst. Eng.* **2020**, *200*, 400–414. [CrossRef]
25. Yolmeh, M.; Jafari, S.M. Applications of response surface methodology in the food industry processes. *Food Bioprocess Technol.* **2017**, *10*, 413–433. [CrossRef]
26. Meggitt, J.W.R.; Moorhouse, A.T. Finite element model updating using in-situ experimental data. *J. Sound Vib.* **2020**, *489*, 115675. [CrossRef]
27. Jiang, D.; Nie, W.; Fei, Q.; Wu, S. Free vibration analysis of composite panels considering correlations of spatially distributed uncertain parameters. *Appl. Math. Model.* **2021**, *98*, 747–757. [CrossRef]
28. Aloisio, A.; Alaggio, R.; Fragiacomo, M. Dynamic identification and model updating of full-scale concrete box girders based on the experimental torsional response. *Constr. Build. Mater.* **2020**, *264*, 120146. [CrossRef]
29. Aloisio, A.; Pasca, D.P.; Alaggio, R.; Fragiacomo, M. Bayesian estimate of the elastic modulus of concrete box girders from dynamic identification: A statistical framework for the A24 motorway in Italy. *Struct. Infrastruct. Eng.* **2021**, *17*, 1626–1638. [CrossRef]
30. Qian, H.; Wu, Y.; Zhu, R.; Zhang, D.; Jiang, D. Modal identification of ultralow-frequency flexible structures based on digital image correlation method. *Appl. Sci.* **2022**, *12*, 185. [CrossRef]
31. Aragon-Rodriguez, F.; Castro-Garcia, S.; Sola-Guirado, R.R.; Gil-Ribes, J.A. Fruit abscission pattern of 'Valencia' orange with canopy shaker system. *Sci. Hortic.* **2019**, *246*, 916–920. [CrossRef]
32. Wang, Y.; Wang, W.; Fu, H.; Yang, Z.; Lu, H. Detachment patterns and impact characteristics of litchi fruit during vibrational harvesting. *Sci. Hortic.* **2022**, *295*, 110836. [CrossRef]
33. Peterson, D.L. Harvest mechanization progress and prospects for fresh market quality deciduous tree fruits. *HortTechnology* **2005**, *15*, 72–75. [CrossRef]

34. Zhou, H.; Wang, X.; Au, W.; Kang, H.; Chen, C. Intelligent robots for fruit harvesting: Recent developments and future challenges. *Precis. Agric.* **2022**, *23*, 1856–1907. [CrossRef]
35. Zhou, J.; Xu, L.; Zhao, J.; Hang, X.; Zhou, H. Effective excitation conditions for the intense motion of the *ginkgo* seed-stem system during mechanical vibration harvesting. *Biosyst. Eng.* **2022**, *215*, 239–248. [CrossRef]
36. Crooke, J.R.; Rand, R.H. Vibratory fruit harvesting: A linear theory of fruit-stem dynamics. *J. Agric. Eng. Res.* **1969**, *14*, 195–209. [CrossRef]
37. Parchomchuk, P.; Cooke, J.R. Vibratory harvesting: An experimental analysis of fruit-stem dynamics. *Trans. ASAE* **1972**, *15*, 598–603.