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Dynamic behavior of the macauba palm (*Acrocomia aculeata*) fruit-rachilla system using the stochastic finite element method

Jéssica Pontes Rangel[1*], Daniel Marçal de Queiroz[1], Francisco de Assis de Carvalho Pinto[1], Cleonice Campos Teixeira[1], Fábio Lúcio Santos[2] and Domingos Sárvio Magalhães Valente[1]

[1]Universidade Federal de Viçosa, Av. Peter Henry Rolfs, s/n, Campus Universitário, 36570-900, Viçosa, Minas Gerais, Brazil. [2]Universidade Federal de Lavras, Lavras, Minas Gerais, Brazil. *Author for correspondence. E-mail: jessica.rangel@ufv.br

ABSTRACT. The search for alternative energy sources has fomented the study of several crops. The macauba palm crop, for instance, has been highlighted because of its particular relevance in Brazil due to its wide distribution across Brazilian territory and its potential for yielding high amounts of oil per cultivated hectare. However, the species is still most commonly harvested via extractivism, which results in low yields. Therefore, we aimed to analyze the dynamic behavior of the fruit-rachilla system when subjected to mechanical vibration to gather baseline information for the subsequent development of macauba harvesting machines. The fruit-rachilla system of the species was modeled for different fruit maturation stages and plant accessions. Natural frequencies and modes of vibration were determined by the stochastic finite element method (FEM), adopting the specific mass and the modulus of elasticity of the system as random variables, which enabled us to compile a dataset of natural frequencies based on the variability of the system properties. The mean values of the natural frequencies obtained in the vibration assays were 26.02 Hz at the green maturation stage and 21.22 Hz at the ripe maturation stage. The mean values of natural frequencies found in the simulation by stochastic FEM, referring to the third mode of vibration, were 26.05 Hz at the green maturation stage and 21.23 Hz at the ripe maturation stage. We concluded that the natural frequencies of the macauba fruit-rachilla system on the basis of different plant accessions showed a decreasing behavior during fruit maturation. The modes of vibration characterized by pendulum displacement did not differ among plant accessions or between fruit maturation stages.

Keywords: biodiesel; stochastic processes; natural frequencies; modes of vibration; palm tree.

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Introduction

The search for new energy alternatives to meet the ever-increasing energy demand worldwide has been devoting considerable importance to research on biodiesel from several sources. The macauba palm [*Acrocomia aculeata* (Jacq.) Lodd. ex Mart.] is among the crops that have been the target of studies with such an aim, being the one crop with the highest potential for oil production per hectare (yields are estimated at 6,200 kg oil ha^{-1}) (Lanes, Costa, & Motoike, 2014). However, the species is still most commonly exploited in Brazil via extractivism, and therefore harvest is largely performed through the direct cutting of bunches and manual extraction of fruits (Pires et al., 2013).

Thus, to increase product quality and quantity of the macauba palm, not only production but also harvest techniques of the species must be improved. Crop mechanization eases harvesting operations by the farmer and overall leads to lower fruit waste, thereby providing the producer with higher cultivation efficiency and rendering the cultivation process less damaging to fruits, thus ultimately improving the quality of the final product (Aguilera, Guzmán, Molina, Soto, & Infante-Amate, 2019).

The mechanical vibration principle has been used in the mechanized harvest of several crops, such as orange, pistachio, coffee, olive, sweet cherry and grape (Pezzi & Caprara, 2009, Coelho, Santos, Pinto, & Queiroz, 2015, Zhou, He, Karkee, & Zhang, 2016, Yang et al., 2019). The principle is based on the transfer of vibrational energy to the fruit to promote its detachment (Santos, Queiroz, Pinto, & Santos, 2010). However, in order for the mechanical vibration principle to be employed, the dynamic properties (e.g., natural frequencies, damping ratio, and modes of vibration) of the studied system must be previously known (Rao, 2011).

Additionally, several aspects may significantly influence the mechanization of the harvest of diverse crops, including macauba. For instance, Srivastava, Goering, and Rohrbach (1996) reported the existence of wide variation among plants of the same crop, which may be modeled by different structures, sizes, shapes and densities.

Hence, due to the great number of factors and the high difficulty of developing harvesting systems, numerical simulation has been used concomitantly with mathematical modeling as an alternative to improve the analysis and comprehension of numerous crops (Villibor, Santos, Queiroz, Khoury Junior, & Pinto, 2016). One of the numerical simulation methods most often used to solve problems with a high degree of complexity is the finite element method (FEM) (Santos, Queiroz, Valente, & Coelho, 2015).

Analysis by the FEM may be deterministic or stochastic. Deterministic analysis is that which uses a previously known set of inputs, not involving each part of the problem to be solved, and results in a single set of outputs (Reale, Xue, Pan, & Gavin, 2015). Stochastic analysis, on the other hand, may use one or more random variables as input, resulting in outputs that are also random. As it involves the sampling of random variables, stochastic analysis is the method that most faithfully reproduces reality (Hien & Noh, 2017). Values are randomized using models that effectively describe the probability distribution of the analyzed parameters (Stefanou, 2009).

Thus, as the macauba palm is a crop with high exploration potential, the aim of this study was to model the dynamic behavior of the fruit-rachilla system for this species – natural frequencies (eigenvalues) and modes of vibration (eigenvectors) – with the goal of gathering baseline information to assist machine designers in projecting harvesting machines that use mechanical vibration in the harvesting process.

Material and methods

The study was conducted at the Laboratory of Machinery Projecting and Artificial Vision (PROVISAGRO, Portuguese acronym) of the Department of Agricultural Engineering of the Federal University of Viçosa (UFV), Minas Gerais State, Brazil. The reference plants used were obtained from the university germplasm bank, located at the UFV experimental farm in Araponga municipality, Minas Gerais State, southeastern Brazil.

Modeling of the macauba fruit-rachilla system was performed to gather information on the natural frequencies (eigenvalues) and their respective modes of vibration (eigenvectors) by the stochastic FEM. The method adopted was based on that used by Coelho, Santos, Queiroz, and Pinto (2016) in the analysis of the dynamic behavior of the fruit-peduncle-branch system of coffee plants.

The analyzed models had the different fruit maturation stages (green and ripe) and plant accessions as specificities. Bunches with the features selected for the assay were collected from palms of different accessions: BD27 – collected at Abaeté municipality, Minas Gerais State, Brazil; BD45 – collected at Unaí municipality, Minas Gerais State, Brazil; BGP29 – collected at Prudente de Morais and Matozinhos municipalities, Minas Gerais State, Brazil; and BGP35 – collected at Mirandópolis municipality, São Paulo State, Brazil.

Values of the geometric, physical and mechanical properties had been previously obtained experimentally and were used as the basis to generate the system geometries (Rangel, Queiroz, Pinto, Santos, & Valente, 2019). The modeled geometry was elaborated using CAD-3D software.

Software Ansys Mechanical APDL version 14.5 was used to perform the steps of the geometric discretization; establishment of the geometric, physical, and mechanical properties and of boundary conditions; solution; and visualization of the results. Tetrahedral elements with ten nodes were used for geometric discretization (Figure 1).

To employ the stochastic FEM, the parameters of the modulus of elasticity and the specific mass of the fruit and rachilla behaved as random variables, whereas dimensional parameters as well as Poisson's ratio behaved as constant values in all models.

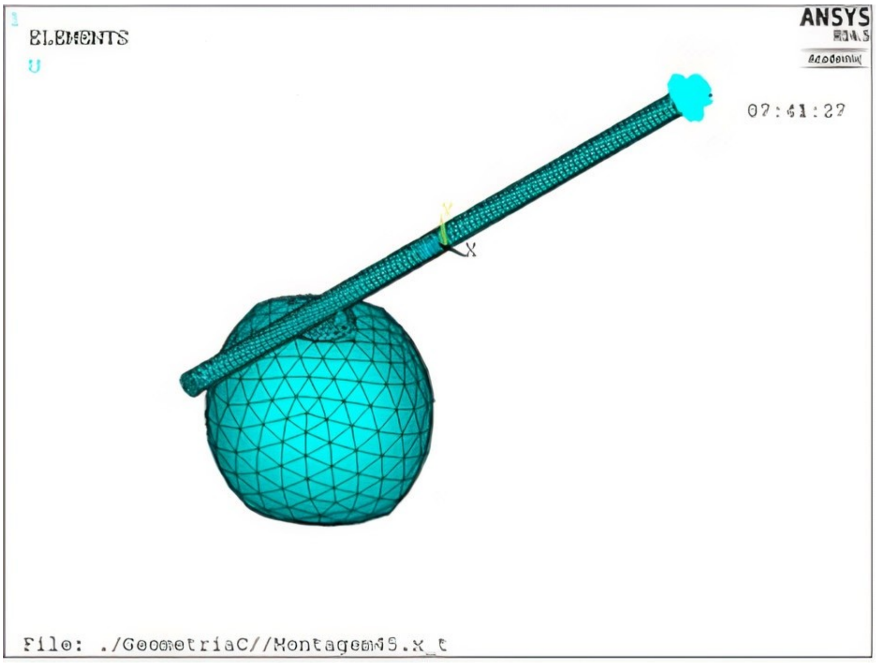

Figure 1. Modeled geometry for simulation of the macauba fruit-rachilla system from accession BD45. The accession was collected at Unaí municipality, Minas Gerais State, southeastern Brazil.

Random variables consisted of eight sets of fifty values each for the modulus of elasticity and specific mass. The sets of values were determined based on the mean values and the respective standard deviations of each parameter of the geometric, physical and mechanical properties previously obtained experimentally. These sets were established by an operation that generates random numbers using Equation (1).

$$V_i = V_0 + s(2N_i - 1) \quad (1)$$

where: V_i = ith random value; V_0 = mean value of the parameter; s = standard deviation of the parameter; and N_i = ith random number, with values between 0 and 1, determined using the algorithm proposed by Press, Vetterling, Teukolsky, and Flannery (2007).

The entire set of values corresponding to the modulus of elasticity was related to the set of specific mass values, thereby generating an iteration with 2500 different models. The input parameters of each model were determined by an algorithm elaborated in FORTRAN 90 language and compiled with a g95 compiler.

All systems elaborated in this study were modeled with diverse degrees of freedom and subjected to undamped free vibration. The algorithm selected in ANSYS Mechanical APDL software to elucidate the dynamic behavior of the fruit-rachilla system was the block Lanczos numerical method, aiming to solve eigenvalue and eigenvector problems, thereby providing the values of natural frequencies and modes of vibration, respectively.

The Monte Carlo method was used to solve the stochastic method. Thus, the obtained results were able to identify the modal features of the macauba fruit-rachilla system considering the different fruit maturation stages and plant accessions.

The implemented tridimensional model, which was elaborated to reproduce a real continuous system, was validated by the observation of real responses analyzed in laboratory assays based on the standard deviation between experimental and simulated natural frequencies using Equation (2).

$$Des = 100\frac{|f_{exp} - f_{fem}|}{f_{exp}} \quad (2)$$

where: Des = deviation, %; f_{exp} = mean natural frequency obtained experimentally, Hz; and f_{fem} = natural frequency obtained by the FEM, Hz.

A LDS (Ling Dynamic System) vibration system composed of a signal generator, an amplifier and an electromagnetic vibrator enabled the vibrational excitation of the real system. Samples were subjected to frequency scanning in the 10–40-Hz range at a scanning rate of 2 octaves per min, peak-to-peak displacement of 1 mm and duration of 90 s. Amplitude variations were determined with high-sensitivity accelerometers (100.7 mV g^{-1} (Eu)). To obtain acceleration data, a routine was elaborated in LabVIEW software (National Instruments Corporation [NIC], 1998) at a 500-Hz sampling rate. This routine commanded the four-channel data acquisition system (model NI cDAQ-9174), which was used as the signal receptor of the accelerometers.

Last, all results were processed aiming to convert all data obtained in the time domain to the frequency domain by using the fast Fourier transform (FFT), thereby enabling the comparison between peaks obtained experimentally and those resulting from simulation.

Results and discussion

Tables 1 and 2 show the specific mass values of the fruit and rachilla of the macauba palm as well as the elasticity modulus of the rachilla according to the study of Rangel et al. (2019). Velloso, Santos, Pinto, Villar, and Valente (2017), evaluating the relationship between the maturation stage and the physical properties of the macauba palm, found values close to those obtained in this work for fruit size. The mean modulus of elasticity values found in this study were 100-fold higher than those obtained by Villar, Pinto, Santos, Grossi, and Velloso (2017).

Table 1. Geometric and physical properties of the macauba fruit from different accessions and at different fruit maturation stages (green and ripe).

Fruit features						
Accession	Maturation stage					
	Green			Ripe		
	Mean diameter (mm)	Specific mass ($g\ cm^{-3}$)		Mean diameter (mm)	Specific mass ($g\ cm^{-3}$)	
		Mean	Standard deviation		Mean	Standard deviation
BD27	38.93	1.17	0.03	41.96	1.24	0.09
BGP29	44.24	1.17	0.08	43.13	1.21	0.10
BGP35	41.42	1.18	0.16	41.50	1.14	0.12
BD45	39.71	1.21	0.04	39.31	1.17	0.10

Note. BD27 – accession collected at Abaeté municipality, Minas Gerais State, Brazil; BGP29 – accession collected at Prudente de Morais and Matozinhos municipalities, Minas Gerais State, Brazil; BGP35 – accession collected at Mirandópolis municipality, São Paulo State, Brazil; BD45 – accession collected at Unaí municipality, Minas Gerais State, Brazil.

Table 2. Geometric and physical properties of the macauba rachilla from different accessions and at different fruit maturation stages (green and ripe).

Rachilla features							
Accession	Maturation stage	Mean diameter (mm)	Specific mass ($g\ cm^{-3}$)		Modulus of elasticity (MPa)		Poisson's ratio
			Mean	Standard deviation	Mean	Standard deviation	
BD27	Green	3.99	0.60	0.10	296	0.52	0.36
	Ripe	3.60	0.60	0.14	189	0.83	0.41
BGP29	Green	3.39	0.54	0.10	319	0.85	0.50
	Ripe	3.59	0.66	0.17	275	0.82	0.45
BGP35	Green	3.96	0.64	0.13	315	0.89	0.39
	Ripe	4.48	0.75	0.13	185	0.89	0.36
BD45	Green	3.44	0.47	0.07	194	0.88	0.38
	Ripe	3.36	0.46	0.12	183	0.92	0.33

Note. BD27 – accession collected at Abaeté municipality, Minas Gerais State, Brazil; BGP29 – accession collected at Prudente de Morais and Matozinhos municipalities, Minas Gerais State, Brazil; BGP35 – accession collected at Mirandópolis municipality, São Paulo State, Brazil; BD45 – accession collected at Unaí municipality, Minas Gerais State, Brazil.

The experimental frequencies were obtained from the frequency spectrum generated with the FFT (Figure 2). The mean values of experimental and simulated natural frequencies from different plant accessions and fruit maturation stages are shown in Table 3.

Both experimental and simulated natural frequencies showed a trend of decreasing values with fruit maturation (Table 3). Similar results have also been obtained in studies on other crops, such as coffee (Santos et al., 2015; Coelho et al., 2016).

The experimental data obtained, used as input parameters in the modeling and simulation of the dynamic behavior of the macauba fruit-rachilla system, showed an increased specific mass of the system and a decreased modulus of elasticity with fruit maturation. Mechanically, the fact that the mass of any system increases while its rigidity decreases is directly related to the reduction in the natural frequency values of the analyzed system.

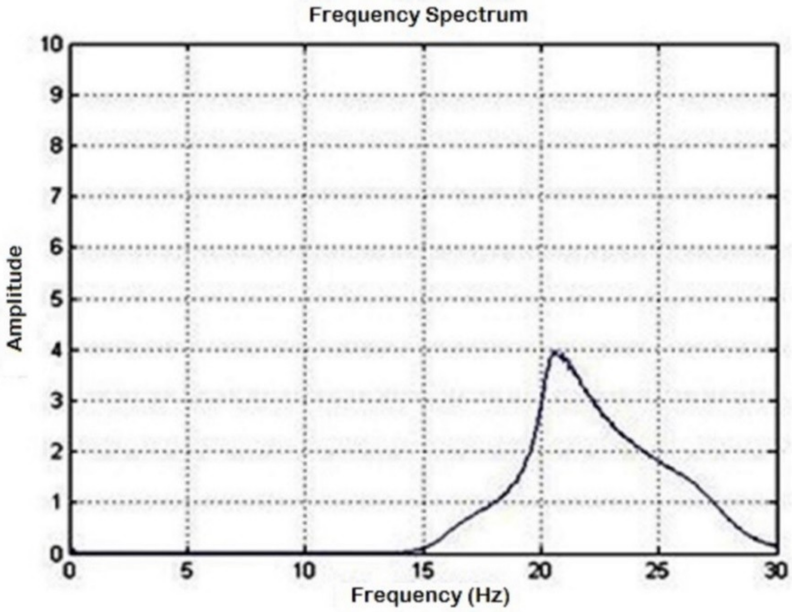

Figure 2. Frequency spectrum of the macauba fruit-rachilla system from accession BD27. The accession was collected at Abaeté municipality, Minas Gerais state, southeastern Brazil.

Table 3. Mean values of experimental and simulated natural frequencies of the macauba fruit-rachilla system from different accessions and at different fruit maturation stages considering the third mode of vibration.

	Frequency (Hz)							
	Green				Ripe			
	BD27	BGP29	BGP35	BD45	BD27	BGP29	BGP35	BD45
Experimental	21.56	24.34	28.15	29.96	18.02	19.17	19.38	28.31
Simulated	23.08	23.89	29.69	27.52	17.91	19.95	20.74	26.33
Deviation (%)	7.05	1.84	5.47	8.14	0.61	4.06	7.02	6.99

Note. BD27 – accession collected at Abaeté municipality, Minas Gerais State, Brazil; BGP29 – accession collected at Prudente de Morais and Matozinhos municipalities, Minas Gerais State, Brazil; BGP35 – accession collected at Mirandópolis municipality, São Paulo State, Brazil; BD45 – accession collected at Unaí municipality, Minas Gerais State, Brazil.

The differences among the natural frequency values of the different accessions may be due to the inherent heterogeneity of the studied crop. The macauba palm remains a little studied species.

The mean standard deviation of all studied scenarios, which was obtained by the stochastic FEM, was 5.15%. Therefore, it may be inferred that the stochastic method is indeed efficient in terms of how much the values of the experimental results approach those of the simulated results.

The mode of vibration, which was pendulum-like, varied neither among plant accessions nor between fruit maturation stages, being the fifth mode of vibration. However, variation was observed in the displacement values. This was due to the decrease in the system rigidity values.

The differences in the responses of the natural frequencies indicate the need for and the importance of using the stochastic FEM to model and evaluate the dynamic behavior of diverse systems, as this method has proven to be an efficient tool in the development of new projects addressing harvesting machinery design.

Conclusion

Both simulated and experimental values of natural frequencies decreased with the transition from the green maturation stage to the mature stage. The modes of vibration, which showed pendulum displacement features, did not differ between fruit maturation stages or among plant accessions. The stochastic finite element method proved to be more efficient than the deterministic method.

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