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Dynamic Behavior of Coffee Branches: an Analysis Using the Finite Element Method

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HIGHLIGHTS

- FEM of the plagiotropic coffee branches;
- Modal analysis;
- Experimental data input.

Abstract: The use of computational simulation techniques is an important tool for the coffee harvesting issues, particularly the finite element method. The method is widely used in the structural analysis of agricultural machinery, as well as in the analysis of the stresses and vibrations of coffee branches and peduncles during the harvesting process. The present study aimed to develop three-dimensional finite element models of the plagiotropic branches of the Catuaí Vermelho variety of Arabica coffee in different positions along the orthotropic branches of the plant; considering high-fidelity models. Additionally, by considering the branches' experimental properties (physical-mechanical), the natural frequencies and vibration modes of the branches were determined by means of computer simulations. First, the geometric properties of the coffee branches were obtained by means of two images taken using a professional camera to obtain the input data of the virtual simulation. For the mechanical properties, it was used a semi-analytical digital scale, to obtain the mass of the specimens. The modulus of elasticity was determined using a universal testing machine. The variability in the simulated natural frequencies could be identified, which was on the order of 30% for the first frequency, regardless of the position of the branch in the plant. These values were lower for the other frequencies. Linear regression fits showed a coefficient of determination, and correlation tests were used to verify the relationship between the values obtained numerically and experimentally, which were validated by using experimental data using the modal analysis techniques.

Keywords: plagiotropic coffee branches; Finite Element Method; Modal Analysis.

INTRODUCTION

The use of mathematical modeling combined with computer simulation techniques is an important tool for performing detailed analyses of coffee harvesting. The finite element method (FEM) has been used to simulate several mechanical and biological systems. By using FEM and through numerical and computational simulation, it is already possible not only to predict the mechanical behavior of the machines but also to identify the stresses and vibrations of the branches and peduncles of the coffee plant during the harvesting process.

The FEM can be applied in agricultural engineering for the structural analysis of agricultural machinery, implements and agricultural product processing and soil mechanics [1-6]. The FEM to evaluate the mechanical behavior of coffee plants and obtained results from numerical simulations using a three-dimensional model for coffee modeling, which showed the feasibility of predicting displacements of coffee branches from static analyses using finite elements [7].

Through models, with greater refinement, is possible to generate significant improvements in the modeling of physical systems, which can be achieved by using a greater number of degrees of freedom [8, 9,10]. The FEM can be used to solve physical problems from mathematical models through simulations with a high degree of reliability. However, experimental tests are necessary to validate the results obtained numerically. Numerical models can be improved and updated when using the experimental results and considering reference values, which allows us to predict the dynamic behavior of the physical systems.

The mathematical modeling of systems with multiple degrees of freedom requires the application of fundamental laws to determine the Equations that govern their behavior [10]. With the advancement of new technologies and greater computational capacity, systems subject to mechanical vibrations can be analyzed by using mathematical modeling to represent the important aspects of a real physical system without excessive complexity. The FEM stands out among the other existing numerical methods because it allows the solution of problems with complex geometries, heterogeneous materials, and different properties in the same domain.

Numerical simulations via finite element analysis for stresses and displacements are usually performed using commercial software that uses numerical packages to solve problems. To perform a finite element analysis, it is necessary to generate a discretized model of the geometry of the studied system [11]. The discretization process consists of the subdivision of a three-dimensional geometric model into small volumes consisting of elements and nodes [12]. Therefore, the FEM can be used to determine the modal properties of a system, which allows the calculation of its natural frequencies and vibration modes from the formulation and solution of eigenvalues and eigenvector problems. The eigenvalues correspond to the natural frequencies of the system, while the eigenvectors refer to the vibration modes of the system and are associated with each natural frequency [13].

However, it is necessary to obtain the physical-mechanical properties of the materials involved in the system to apply the FEM. To perform numerical simulations of the dynamic behavior of coffee plants, [7,14,15] determined the input parameters of the system, such as the modulus of elasticity, shear modulus, Poisson ratio, and density. [14,16] characterized the physical properties of macaw palm fruits and rachilla and concluded that such factors directly influence the results of the simulations, as they are related to the stiffness and mass of the systems.

The main machines used in agriculture involve mechanical vibrations, such as the harvester machines used in the mechanized harvesting of coffee [17,18]. This process needs to be better studied from aspects such as the influence of stem vibration and harvester speed on the mechanized coffee harvesting process [3]. Representative models have been shown to be effective in decision-making regarding the coffee management and harvesting process [18,19]. According to [20] simulations can eliminate the need for field experiments and have become increasingly accurate.

The natural frequencies, mode shapes, and vibration amplitudes have been studied using numerical/computational methods to evaluate the dynamic behavior of the coffee fruit-peduncle-branch system [7,17, 18, 19, 21, 22, 23]. The results of the proposed numerical models indicate that the vibration modes associated with the natural frequencies at specific intervals favor coffee harvesting and consider its different maturation stages. The results found are consistent compared to experimental analyses using actual plants, which demonstrates the potential use of the methods. However, due to the complexity in modeling the branches, advances in the established models are extremely necessary to confer greater reliability and representativeness.

Thus, the aim of this work was to develop three-dimensional models of finite elements of plagiotropic branches of the Catuaí Vermelho variety of Arabica coffee in different positions along the orthotropic branches of the plant by considering high-fidelity models. Additionally, by considering the branches'

experimental properties (physical-mechanical), the natural frequencies and mode shapes of the branches were determined by means of computer simulations. We validate the results using experimental data determined by experimental modal analysis techniques.

MATERIALS AND METHODS

We used a total of 15 samples of plagiotropic branches of the Catuaí Vermelho IAC 144 variety without leaves and fruits, with 5 samples for each treatment. From the position of the plagiotropic branches in relation to the orthotropic branches of the plant, we defined the following treatments: upper third, middle third, and lower third, as presented in Figure 1.

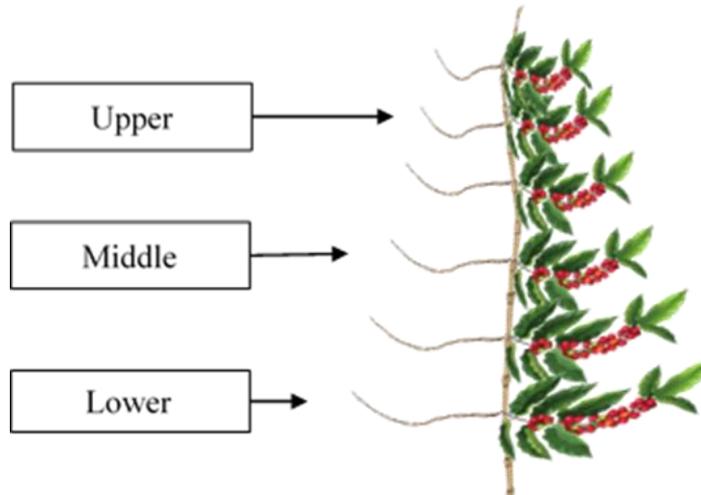


Figure 1. Positions of branches on the plant

Geometric properties of the branches

The first step of this study involved obtaining the geometric properties of the branches by means of two images – one vertical and the other horizontal – taken with a professional camera and showing the three coordinates (XYZ) necessary for later modeling. As shown in Figure 2, we used two graduated grids (mm) positioned perpendicular to each other as a background for the images.

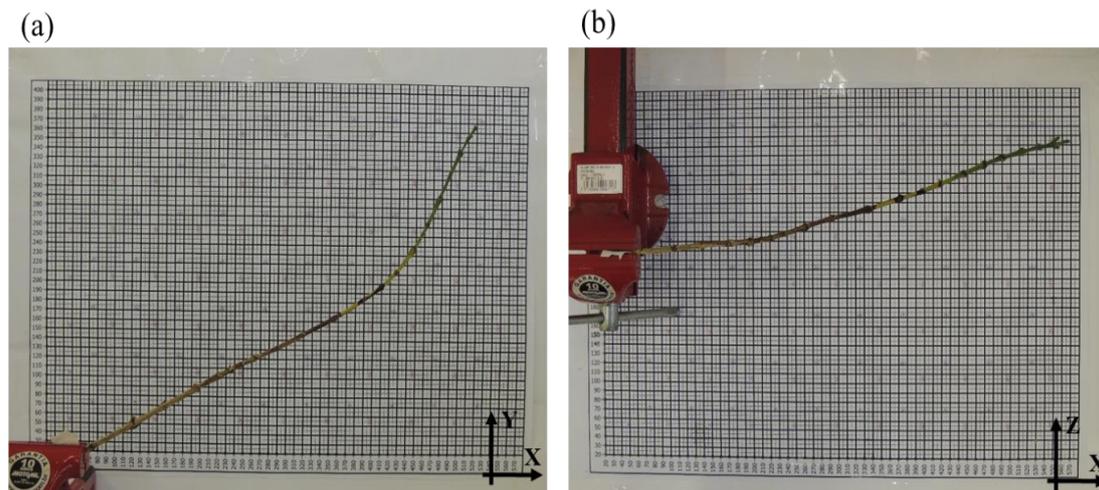


Figure 2. Images of the branches taken with a graduated grid background (mm): (a) Horizontal orientation (XY - front view) and (b) vertical orientation (XZ - top view).

In a standardized manner, the coordinates and diameters of the representative points of the branch were extracted: anterior and posterior to the node and on the node. The three-dimensional coordinates of the branches were collected, one by one, by using the open-source software ImageJ [24].

Mechanical properties of the branches used in the simulations

The experimental determination of the mechanical properties was performed in a step subsequent to the collection of the geometric properties, as they are destructive tests. Specimens were prepared from the fifteen samples of plagiotropic branches collected along the plant – corresponding to the treatments (upper, middle, and lower in the plant) – to determine the mechanical properties. Two specimens were collected from each sample, one closer to the cut performed next to the orthotropic branch and the other near the free end of the branch.

The masses of the specimens were determined using a semianalytical digital scale, model AD500, manufactured by Marte Científica® with a resolution of 0.001 g. The immersion method with a 10 mL beaker was used to determine the volume of the specimens. The density of each sample was obtained by the ratio between the experimental values of mass and volume.

The modulus of elasticity was determined using a universal testing machine, model EMIC 23-20, manufactured by Instron® and equipped with a maximum load cell of 20 kN. The specimens were subjected to tensile tests parallel to the branch fibers, which was fixed by clamps at its ends and subjected to loading in its central region. A preload of 2 N was applied for pre-tensioning of the specimen at a speed of 0.01 m.min⁻¹; the test was ended when there was a deviation from linearity after reaching the maximum stress.

The authors in [20] obtained Poisson ratio values of 0.09 and 0.25 for the Catuaí Vermelho (IAC 144) variety in compression tests for the stem and tensile tests for the branches, respectively. [7] determined the Poisson ratio obtained from stem samples from Catuaí Vermelho (IAC 144). By using images before and after compression tests, the authors defined a mean Poisson ratio of 0.37 with a standard deviation of 0.1.

Given the difficulty in correctly determining the Poisson ratio and the different results available in the literature for this property, an average value found in the literature [14, 15, 16, 20] was used for this mechanical property as 0.30. It is noteworthy that for the purpose of simulation in this study, the sample material was considered to be homogeneous and isotropic.

We subjected the values determined for the modulus of elasticity and density to analysis of variance according to a completely randomized design (CRD) and considering the different positions in the plant (Figure 1) for each natural frequency evaluated. We analyzed the means by using the Tukey test at a significance level of 5%.

Modeling, convergence analysis and simulation

We modeled the branches based on the points collected in the computer-aided design (CAD) environment of the Siemens NX® software Version 9.0. We performed the union of the modeled circles by using parameterized surfaces with G2 continuity restriction (curvature). The boundary conditions of the system restricted the model base to six degrees of freedom, which represented the fixation of the plagiotropic branch next to the orthotropic branch of the plant.

By considering a tetrahedral geometry of 10 nodes for the elements, the meshes were analyzed at the third natural frequency to verify the convergence of the results in relation to the numerical simulations. Different elements of sizes were evaluated between 3 and 13 mm and an interval of 2 mm. The results were compared until they converged satisfactorily, given a reasonable result associating with a low computational cost.

After the discretization of the models, The simulations were in the simulation environment of the Siemens NX® software Version 9.0 by using the following input parameters: modulus of elasticity, density, and Poisson ratio. The block Lanczos algorithm was used to solve the problems of the eigenvalues and eigenvectors of the system, which yielded the natural frequencies and vibration modes of the systems, respectively.

Eigenvalues and eigenvectors

By applying external forces to the system, it is possible to model the system in matrix form represented by differential equations with multiple degrees of freedom, according to Equation 1.

$$[m]\{\ddot{x}\} + [c]\{\dot{x}\} + [k]\{x\} = \{F\} \quad (1)$$

Where $\{F\}$ is the force vector, $[m]$ is the mass matrix, $[c]$ is the damping matrix, $[k]$ is the stiffness matrix, $\{x\}$ is the displacement vector, $\{\dot{x}\}$ is the velocity vector, and $\{\ddot{x}\}$ is the acceleration vector. For free and undamped vibrations, Equation 1 can be simplified, resulting in Equation 2.

$$\begin{bmatrix} m_{11} & m_{12} & \cdots & m_{1n} \\ m_{21} & m_{22} & \cdots & m_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ m_{n1} & m_{n2} & \cdots & m_{nn} \end{bmatrix} \begin{Bmatrix} x_{11} \\ x_{21} \\ \vdots \\ x_{n1} \end{Bmatrix} + \begin{bmatrix} k_{11} & k_{12} & \cdots & k_{1n} \\ k_{21} & k_{22} & \cdots & k_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ k_{n1} & k_{n2} & \cdots & k_{nn} \end{bmatrix} \begin{Bmatrix} x_{11} \\ x_{21} \\ \vdots \\ x_{n1} \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \\ \vdots \\ 0 \end{Bmatrix} \quad (2)$$

Equation 2 represents the system's natural vibration conditions. The state of natural vibration can be called natural modes or mode shapes, and the vibration frequencies are natural frequencies of the system. By assuming that the free vibrations are harmonic, the eigenvalues and eigenvectors can be obtained by rewriting the system according to Equation 3, which represents the displacement of the system.

$$\{x\} = \{\varphi\}_i e^{i\omega_i t} = \{\varphi\}_i (\cos \omega_i t + i \sin \omega_i t) \quad (3)$$

Where $\{\varphi\}_i$ represents the eigenvector associated with the i -th natural frequency of the system, ω_i corresponds to the angular frequency (in $\text{rad}\cdot\text{s}^{-1}$), and t is associated with time (s). The natural frequencies and vibration modes can be obtained by solving the problem of eigenvalues and eigenvectors after derivation of Equation 3 in relation to time and substitution in Equation 2. Thus, Equation 4 is obtained, which is recognized as an eigenvalue problem [13].

$$(-\omega^2[m] + [k])\{\varphi\}_i = \{0\} \quad (4)$$

Equation 4 presents a nontrivial solution only if the determinant of the matrix $(-\omega^2[m] + [k])$ is equal to zero [8, 13, 25].

Experimental modal analysis

The natural frequencies of the samples were experimentally determined using the frequency response function (FRF) via an impact test. The branches were instrumented with unidirectional accelerometers, vertically fixed with plastic clamps. The impact hammer used has the following specifications: model PCB 086C03, manufactured by PCB Piezotronics™, with a "super soft" tip and force sensor. Through an acquisition module, model NI cDAQ-9174, manufactured by National Instruments™, the acceleration data and the impact hammer data were collected using the Sound and Vibration package of LabView® software.

The branches were embedded in a vise and applied the impact to obtain the FRF in the central part by using the acceptance/rejection criterion based on the coherence obtained in 5 effective impacts. The tests were rejected considering the coherence values if they were not greater than 0.8.

The magnitude data obtained with the FRF was converted into decibels (dB) and subsequently filtered them (with a high pass filter), which allowed the passage of the high amplitude frequencies and attenuated the amplitude of the frequencies below the cutoff amplitude of 5 dB. The graphs were plotted and found that the curve became unstable and lacked prominent peaks after the third peak. Thus, the first three natural frequencies were selected, which corresponded to the first three peaks.

Validation of the models

The experimental natural frequency values of each of the first three natural frequencies were subjected to analysis of variance, according to a CRD. By considering the plant position factor, the experimental natural frequencies were analyzed using the Tukey test at a significance level of 5%. The study of the natural frequency means obtained along the plant resulted in the following validations of the proposed models.

For each sample, the natural frequencies obtained by the numerical simulations, corresponding to the first three vibration modes, were compared with the experimental natural frequency values. We validated the proposed models by linear regression and correlation tests, with the results presented in [30].

From the linear regression, we analyzed the angular coefficient values of the fitted curve and the coefficient of determination (R^2). The Pearson correlation test and the p value at a significance level of 10% evaluated the correlation between numerical and experimental values. The software R was used to perform the statistical analyses.

RESULTS AND DISCUSSION

Table 1 presents the geometrical properties obtained experimentally. The values of the XY length, XZ length and diameters (maximum, minimum and mean) for the upper third, middle third and lower third are presented.

Table 1. Geometrical properties of the study samples

Position in the plant	Length (XY) [mm]			Diameter [mm]
	Minimum	Maximum	Mean	Mean
Upper	401.98	538.17	470.08	6.86
Middle	439.64	524.03	481.36	5.99
Lower	414.30	541.59	477.94	6,03

Position in the plant	Length (XZ) [mm]			Diameter [mm]
	Minimum	Maximum	Mean	Mean
Upper	403.62	536.38	469.99	6.86
Middle	438.17	525.79	481.97	5.99
Lower	408.88	538.38	473.63	6.03

Table 2 shows the mean values of the physical-mechanical properties obtained from the two specimens made for each experimental unit. The values found for the modulus of elasticity and density were used in the correlation between experimental and simulated data, sample by sample.

Table 2. Mechanical properties of the study samples: modulus of elasticity (E), in GPa, and density (ρ), in g.cm⁻³

Sample	E (GPa)	ρ (g.cm ⁻³)
Am_sup1	1.25	1.007
Am_sup2	0.70	0.933
Am_sup3	1.13	0.921
Am_sup4	1.08	0.926
Am_sup5	0.70	0.922
Am_med2	0.73	0.972
Am_med3	1.26	0.962
Am_med4	1.11	0.998
Am_med5	1.19	0.914
Am_inf1	1.15	0.890
Am_inf2	1.22	0.937
Am_inf3	1.01	0.960
Am_inf4	1.12	0.964
Am_inf5	1.56	0.945

For the upper third, the mean density was 0.941 g.cm⁻³ with a standard deviation of 0.037 g.cm⁻³ and the mean modulus of elasticity was 0.97 GPa with standard deviation of 0.25 GPa. The middle third showed mean density of 0.953 g.cm⁻³ with a standard deviation of 0.036 g.cm⁻³ and a mean modulus of elasticity equal to 1.14 GPa with standard deviation of 0.25 GPa. For the lower third, the mean density value was 0.939 g.cm⁻³ with a standard deviation of 0.030 g.cm⁻³ and the mean modulus of elasticity was 1.21 GPa with

standard deviation of 0.21 GPa. The means found for the different positions in the plant, both for the density and for the modulus of elasticity, were not significantly different according to Tukey's test at a significance level of 5%. The small number of samples may explain the high standard deviation for the means found.

The average density equal to 0.900 g.cm^{-3} and a mean modulus of elasticity equal to 1.94 GPa with standard deviation of 0.62 GPa for Catuaí Vermelho IAC 144 branches, was determined [15]. Factors such as variety, age, climatic conditions, and types of management in addition to different methods for obtaining the properties, may explain the difference between the values obtained by the authors and those found in this study. The density average value of 0.978 g.cm^{-3} and a mean modulus of elasticity ranging between 1.79 GPa and 3.56 GPa for the Catuaí Vermelho UFV-2237 variety [25]. The bending method used by the authors and the variety adopted, which were different from those used in this study, may explain the divergence between the values found.

The elements size was defined using a convergence analysis, as presented in Figure 3, considering the third vibration mode. In this way, the convergence analysis showed results from element sizes below 5 mm, according to Figure 3. The grade 3 polynomial curve had a coefficient of determination of 97.04%.

For the elements with a size equal to 5 mm, we obtained a frequency of 29.49 Hz with a mesh containing 3353 elements. The refinement for the size equal to 3 mm showed a frequency of 29.60 Hz, which corresponds to an increase of 0.37% for an increase in mesh size greater than 108%. The increase in the mesh size directly impacts the computational cost required for the simulation; therefore, we chose an element size equal to 5 mm.

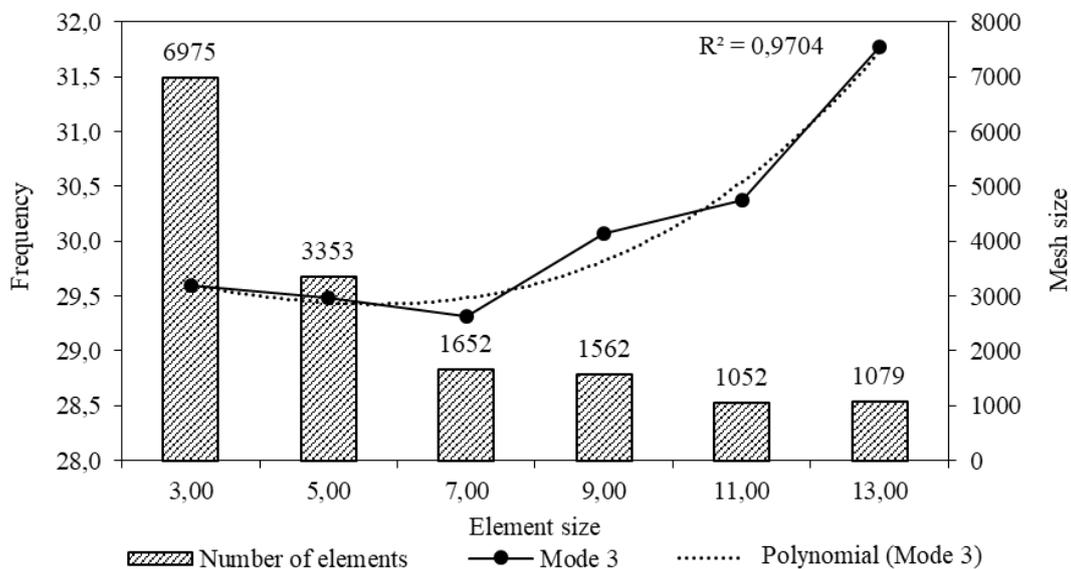


Figure 3. Mesh convergence analysis for the 3rd vibration mode. Natural frequency in Hz and element size in mm.

The details of the discretization of a sample are presented in Figure 4.

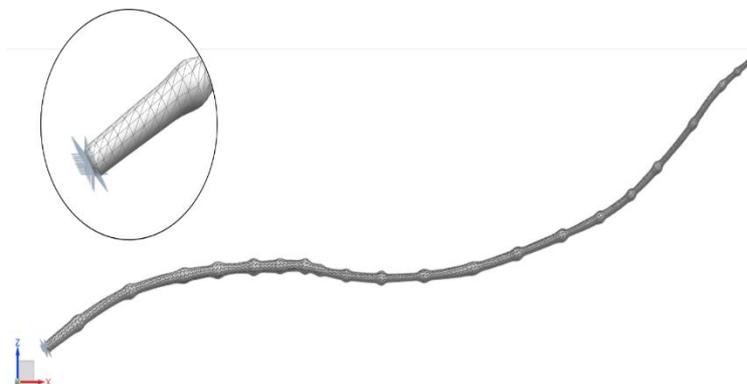


Figure 4. Discretized sample of the branch of the coffee plant.

After the simulations, it was observed groups of mode shapes with very similar frequency values related to bending modes for lateral vibration. According to [20] obtaining vibration modes in different directions for the same frequency is expected for a system in free vibration. Thus, the frequency values corresponding to the lateral vibration mode in the plane were considered at which the experimental modal analysis performed using by impact hammer. In Figure 5, an example of the result obtained in the simulations is presented.

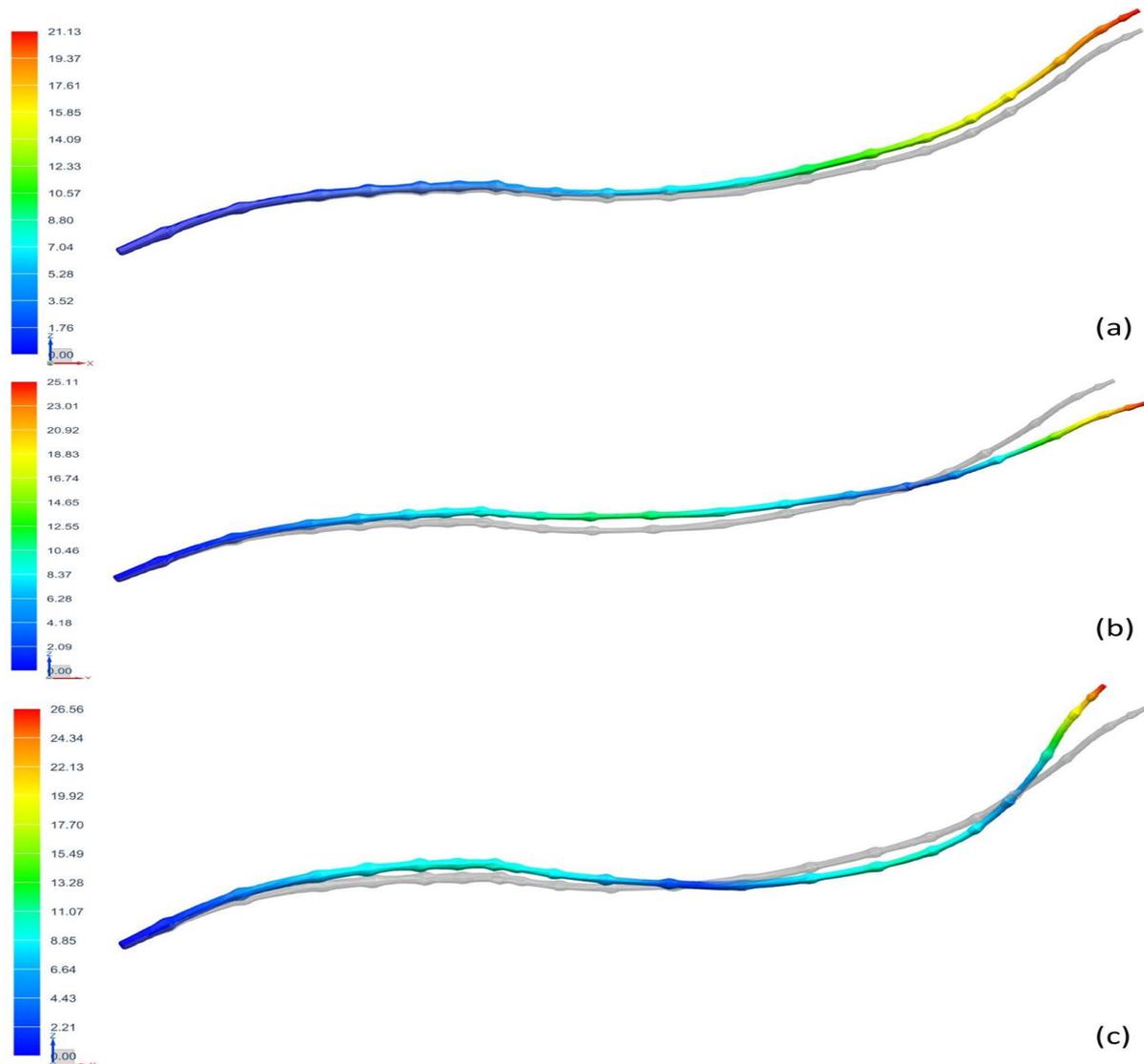


Figure 5. Example of results obtained in the simulations: (a) first natural frequency; (b) second natural frequency; and (c) third natural frequency.

The natural frequencies obtained experimentally were subjected to analysis of variance, with the means presented in Table 3. Significant differences at a significance level of 5% were not observed in different positions in the plant for any of the natural frequencies studied (ω_{n1} , ω_{n2} , and ω_{n3}).

Table 3. Mean natural frequencies for each position in the plant, in Hz.

Position in the plant	Mean natural frequency (Hz)		
	ω_{n1}	ω_{n2}	ω_{n3}
Upper	6.45	20.48	43.73
Middle	4.92	15.98	36.15
Lower	5.72	18.12	48.13

Given that the natural frequencies determined experimentally for different positions in the plant did not show significant differences, the first, second, and third natural frequencies were determined, the mean natural frequencies, and percentage variation between the numerical and experimental values, as shown in Table 3.

The first natural frequency showed the highest percentage variation between the numerical and experimental natural frequencies. Values equal to -31%, -26%, and -29% were found for the upper third, middle third, and lower third, respectively. The second frequency showed the best fit between the models, with -1% obtained for the upper third, 1% for the middle third, and -7% for the lower third. For the third frequency, values of 13%, 7%, and -15% were observed for the upper, middle, and lower thirds, respectively.

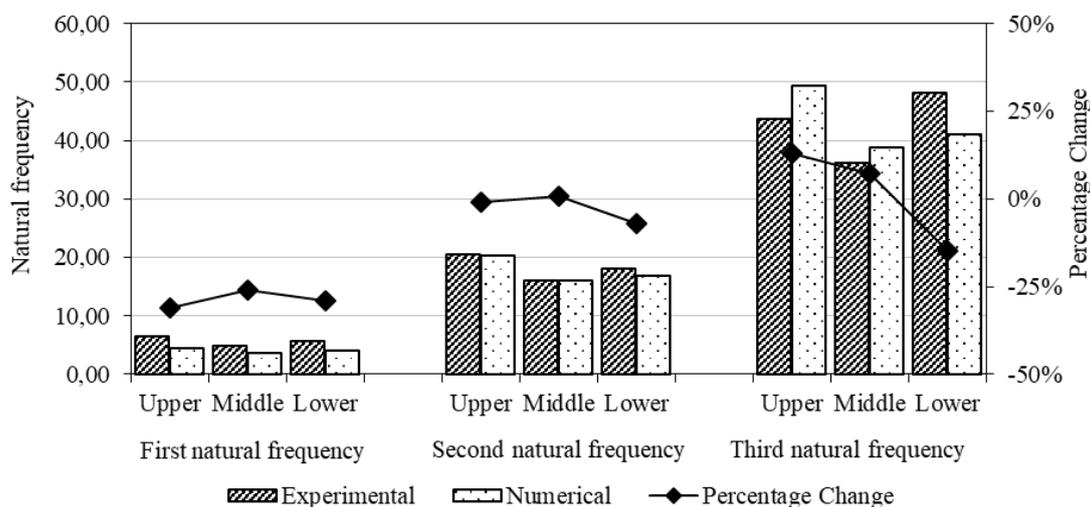


Figure 6. Comparison between experimental and numerical mean natural frequencies (in Hz) for each third of the plant, as well as the percentage variation between numerical and experimental natural frequencies.

The high variability in the physical-mechanical properties adopted as input parameters in the simulations may explain the divergence between the experimental and numerical results, which was more pronounced for the first natural frequency, as shown in Figure 6. In addition, the discrepancy between the results may be related to the imprecision of the methods used to determine the mechanical properties since they are considered systems of complex physiology that are in the development phase, with different topologies within the same sampling field [15, 17, 21, 26].

For the first natural frequency, it was obtained a mean experimental value of 5.70 Hz and a mean numerical value of 4.04 Hz, which corresponds to a mean percentage variation of 29%. The numerically determined values were, on average, lower than the experimental values. The second natural frequency had a mean experimental value of 18.19 Hz and a mean numerical value of 17.73 Hz. The mean percentage variation for the second natural frequency was 3%, and the numerical values were below those obtained experimentally. The values observed for the third natural frequency had a mean experimental value of 42.67 Hz and a mean numerical value of 43.03 Hz. The mean percentage variation was 1%, with the numerical value higher than that obtained experimentally.

In the study of the natural frequencies of the plagiotropic branches of the Catuaí Vermelho variety, [23] found values of 14.57, 16.83, and 19.45 Hz for the minimum, mean, and maximum values, respectively. The range of natural frequencies we found corresponds to the values obtained for the second frequency determined in this study.

The experimental studied performed by [21] the effect of the frequency and amplitude of vibration on coffee fruit harvesting, and the authors observed that the frequency of 26.67 Hz tended to have a higher mean harvesting efficiency for the fruits in the mature stage. In addition, the authors concluded that the fruits in stages prior to ripening or cherry tended to have lower harvesting efficiency for this frequency. Thus, it is possible to relate the values found in the second natural frequency of this study with a better harvesting efficiency.

The authors in [24] had also evaluated the influence of the modulus of elasticity on the simulated natural frequency using the FEM. By using an algorithm, they compared the increase or decrease in the value of the modulus of elasticity with the percentage deviation between the experimental and simulated frequencies. The

geometry and physical-mechanical properties of the model used by the authors were determined by [15], with the following specifications: diameter of 5.06 mm, density of 0.90 g.cm⁻³, and Poisson ratio of 0.34. For better representation and approximation of the actual system, the method used by the authors can be used to evaluate the influence of the physical-mechanical properties in simulated models.

Thus, to evaluate the relationship between the natural frequency values obtained numerically and those obtained experimentally, linear regression analyses and Pearson's correlation tests were performed, as shown in Table 4.

Table 4. Linear regression equation ($f(x) = bx + a$), coefficient of determination (R^2), and Pearson correlation coefficient (ρ) between numerical and experimental values for each sample.

Sample	Linear regression equation	R^2	ρ	p-value
Am_sup1	$f(x) = 0.8822x + 3.6327$	1.00	1.00	0.0311
Am_sup2	$f(x) = 0.7553x + 4.6894$	0.99	0.99	0.0698
Am_sup3	$f(x) = 0.6352x + 4.8608$	0.97	0.99	0.0698
Am_sup4	$f(x) = 1.0227x + 1.0077$	1.00	1.00	0.0270
Am_sup5	$f(x) = 0.8519x + 1.9673$	0.99	1.00	0.0606
Am_med1	$f(x) = 0.8975x + 1.6655$	1.00	1.00	0.0062
Am_med2	$f(x) = 0.8078x + 4.4529$	0.93	0.97	0.1657
Am_med3	$f(x) = 0.8776x + 0.1561$	0.99	1.00	0.0621
Am_med4	$f(x) = 0.9262x + 2.3278$	1.00	1.00	0.0090
Am_med5	$f(x) = 0.9178x - 0.1765$	0.99	0.99	0.0745
Am_inf1	$f(x) = 1.2339x + 2.8352$	1.00	1.00	0.0069
Am_inf2	$f(x) = 1.2411x - 1.0381$	0.99	1.00	0.0632
Am_inf3	$f(x) = 0.819x + 2.1078$	1.00	1.00	0.0163
Am_inf4	$f(x) = 0.9632x - 0.8722$	0.97	0.99	0.1084
Am_inf5	$f(x) = 1.6956x - 2.7144$	1.00	1.00	0.0361

Through the regression analysis, it was possible to evaluate whether the numerically proposed model faithfully describes the actual system with the data obtained experimentally. The fit of the proposed lines to the models showed little dispersion, with R^2 values greater than 0.99 in twelve of the fifteen samples. The results show that the geometric models are optimally similar to the branch topology. In addition, the analysis of the slopes (b) of the linear regression equations allowed us to evaluate the relationship between the dependent variable and the independent variable because values of b close to 1 (one) indicate a greater association between the variables. The results found for the Pearson correlation test (ρ) were close to or equal to one for all samples analyzed, which represents a perfect positive correlation between the two variables. For a significance level of 10%, we could conclude that there was a significant relationship between the numerical and experimental variables for all samples, except for Am_med2 and Am_inf4.

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Similarly, [20] experimentally and numerically determined the natural frequencies of the coffee plant of the Catuaí Vermelho (IAC 144) cultivar. To experimentally obtain the natural frequencies, the authors used a free vibration system so that the samples did not touch the soil. Through the FRF, accelerometers installed throughout the plant detected a higher incidence of natural frequency peaks between 10 Hz and 30 Hz. In turn, they determined the natural frequencies and vibration modes through the generation of representative models and simulation via the FEM. The input parameters in the simulation used by the authors were experimentally determined, sample by sample. The authors found an association between experimental and simulated data through linear regression analysis and correlation tests, which validated the proposed models.

Considering the deterministic FEM, the high variability and complexity found in obtaining the geometric, physical, and mechanical properties of the coffee system directly influence the simulated results [17,21]. To verify the effect of the values of modulus of elasticity and density on the results of the proposed models' simulations, [18] used the stochastic FEM to study the fruit-peduncle-branch system. The authors concluded that the natural frequencies increased with an increasing modulus of elasticity or a decreasing density of fruits, peduncles, and branches.

In addition, the simplification of the mechanical properties of the materials by considering them homogeneous and isotropic materials was considered a predominant factor in the differences found in the study by [7]. The authors also observed that branches of different sizes along coffee plants exhibit different patterns of mechanical stiffness. According to [13], differences between the density and stiffness of the system affect the system vibration mode.

Thus, stochastic methods can be used to analyze how the physical-mechanical properties affect the results of the simulations, in which input data are selected by random values and a set of results is obtained for a given parameter [27, 28, 31, 32]. In this way, the obtained results in the present research could serve as reference to use different approach to quantify uncertainties from the inherent variability of the Coffee plant. Uncertainty analysis using stochastic modeling with low computational cost could use the range parameters obtained here [29, 33, 34].

CONCLUSIONS

Regarding the study of the dynamic behavior of coffee branches using the FEM, the following conclusions were reached:

- For the first natural frequency, the natural frequencies simulated using the FEM showed deviations of -31%, -26%, and -29% for the upper, middle, and lower thirds of the plant, respectively. The high variability in the physical-mechanical properties used as input parameters in the simulations may explain the high deviations found for the first natural frequency.
- The second natural frequency presented the best fit between the models and had percentage variations of -1%, 1%, and -7% for the upper, middle, and lower thirds, respectively
- For the third frequency, we observed percentage variations with values equal to 13%, 7%, and -15% for the upper, middle, and lower thirds, respectively.
- Linear regression fits showed a coefficient of determination above 0.99 in twelve of the fifteen samples. In addition, correlation tests indicated that there was a significant relationship between the numerical and experimental variables.

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