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DETERMINATION OF PHYSICAL PROPERTIES AND SIMULATION OF DYNAMIC BEHAVIOR OF COFFEE PLANTS

Lavras – MG
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Tese apresentada à Universidade Federal de Lavras, como parte das exigências do Programa de Pós-Graduação em Engenharia Agrícola, área de concentração Máquinas e Mecanização Agrícola, para obtenção do título de Doutora.

Prof. Dr. Ricardo Rodrigues Magalhães
Orientador

Prof. Dr. Fábio Lúcio Santos
Coorientador

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Ficha catalográfica elaborada pelo Sistema de Geração de Ficha Catalográfica da Biblioteca Universitária da UFLA, com dados informados pelo(a) próprio(a) autor(a).

Velloso, Nara Silveira.
Determination of physical properties and simulation of dynamic behavior of coffee plants / Nara Silveira Velloso. - 2020.
77 p. : il.

Orientador(a): Ricardo Rodrigues Magalhães.
Coorientador(a): Fábio Lúcio Santos.
Tese (doutorado) - Universidade Federal de Lavras, 2020.
Bibliografia.

1. Colheita mecanizada de café. 2. Vibrações mecânicas. 3. Propriedades físicas de plantas de café. I. Magalhães, Ricardo Rodrigues. II. Santos, Fábio Lúcio. III. Título.

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APROVADA em: 20 de Julho de 2020.

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Lavras – MG
2020

AGRADECIMENTOS

Agradeço aos meus pais Helenice e Antônio, por sempre me apoiarem, me incentivarem e por, principalmente, me ampararem e serem alento em todas as adversidades. Amo vocês.

Agradeço também aos meus irmãos Sidney e Sérgio por, mesmo distantes, não medirem esforços em me ajudarem quando eu preciso.

Aos meus sobrinhos Lara, Felipe, José Augusto e Francisco por todo carinho e momentos de felicidade.

Agradeço ao meu namorado Márcio, que não mede esforços para me apoiar, incentivar e ajudar.

Agradeço aos familiares e amigos que apoiaram e torceram por mim.

Ao meu orientador Professor Ricardo Magalhães, agradeço pelo incentivo e orientação.

Ao meu coorientador Professor Fábio Lúcio, que é parte fundamental da minha trajetória acadêmica, minha eterna gratidão.

Agradeço ao professor Rubens e à equipe do INOVACAFÉ, que cederam as amostras de plantas e auxiliaram na seleção e corte das amostras.

Agradeço ao técnico de laboratório Bruno Vicentini, que auxiliou na etapa laboratorial e na fabricação dos corpos de provas.

Ao colega de pós-graduação Alexandre Rezende, agradeço pela colaboração com o trabalho.

À Universidade Federal de Lavras, ao Departamento de Engenharia e ao Programa de Pós-graduação em Engenharia Agrícola, agradeço pela oportunidade de realizar o doutorado e complementar minha formação acadêmica.

O presente trabalho foi realizado com apoio da Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES).

Muito obrigada!

“Por que se chamavam homens

Também se chamavam sonhos

E sonhos não envelhecem.”

(Clube da Esquina)

GENERAL ABSTRACT

The objective of this work was to study the dynamic behavior of coffee plants, in order to analyze their behavior during harvesting process, from numerical simulations, using a previously developed model. To support the simulations, the physical and mechanical properties (elasticity modulus, Poisson's ratio and specific mass) of specimens from the trunks and branches of coffee plants were determined in the laboratory, using tensile and compression tests in an universal testing machine. Such characteristics served as a basis to extract the natural frequencies and the modes of vibration (modal properties) from numerical simulations, which were performed using the deterministic Finite Element Method. To validate the model used, laboratory tests of free vibration using samples of whole plants were performed and the values found in the laboratory tests were compared statistically with the results found in the numerical simulations. The methodologies used in all stages of the research allowed evaluating the dynamic behavior of coffee plants when subjected to mechanical vibrations, which can assist in the development and adjustment in the use of mechanisms that perform mechanized harvesting in coffee plantations. The results obtained indicate values of elasticity modulus, for the trunk, of 1,090.94 MPa in the longitudinal direction and 108.60 MPa in the transversal direction; elasticity modulus of the branches, performed from tensile tests in the longitudinal direction, of 507.72 MPa. Poisson's ratio values, determined by direct measurements, were 0.25 for the trunk and 0.09 for the branches. Specific mass values found were 1070.05 kg.m^{-3} for the trunk and 1036.33 kg.m^{-3} for the branches. Frequency values found in the laboratory tests were concentrated in the range between 10 Hz and 30 Hz. This work took into account real aspects of coffee plants, such as their anisotropy and the use of a model built from reverse engineering, which represents an advance in research that simulates the dynamic behavior of coffee plants during the harvesting process.

Keywords: Mechanized harvesting, coffee crop, mechanical vibrations, modal parameters.

RESUMO GERAL

O objetivo deste trabalho foi estudar o comportamento dinâmico do cafeeiro, para analisar seu comportamento durante a colheita, a partir de simulações numéricas, utilizando um modelo previamente desenvolvido. Para dar suporte às simulações, as propriedades físicas e mecânicas (módulo de elasticidade, coeficiente de Poisson e massa específica) de corpos de provas provenientes dos troncos e ramos de cafeeiros foram determinadas em laboratório, a partir de ensaios de tração e compressão em máquina de ensaios universal. Tais características serviram de base para extrair as frequências naturais e os modos de vibração (propriedades modais) de simulações numéricas, que foram realizadas utilizando o Método de Elementos Finitos determinístico. Para validação do modelo utilizado, testes laboratoriais de vibração livre, utilizando amostras de plantas inteiras foram realizados e os valores encontrados nos ensaios laboratoriais foram comparados estatisticamente com os resultados encontrados nas simulações numéricas. As metodologias utilizadas em todas as etapas da pesquisa permitiram avaliar o comportamento dinâmico do cafeeiro quando submetido a vibrações mecânicas, o que pode auxiliar no desenvolvimento e ajuste no uso de mecanismos que realizam a colheita mecanizada em lavouras cafeeiras. Os resultados obtidos indicam valores de módulo de elasticidade, para o tronco, de 1.090,94 MPa no sentido longitudinal e 108,60 MPa no sentido transversal; módulo de elasticidade dos galhos, realizado a partir de ensaios de tração no sentido longitudinal, de 507,72 MPa. Valores do coeficiente de Poisson, determinada por medidas diretas, foram de 0,25 para o tronco e 0,09 para os ramos. Valores de massa específica encontrados foram de 1070.05 $kg.m^{-3}$ para o tronco e 1036.33 $kg.m^{-3}$ para os ramos. Por fim, valores de frequências encontradas nos testes de laboratório foram concentrados no intervalo entre 10 Hz e 30 Hz. Este trabalho levou em consideração aspectos reais das plantas de café, como sua anisotropia e a utilização de um modelo construído a partir de engenharia reversa, o que representa um avanço nas pesquisas que simulam o comportamento dinâmico de cafeeiros durante o processo de colheita.

Palavras-chave: Colheita mecanizada, cafeicultura, vibrações mecânicas, parâmetros modais.

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SUMMARY

PART ONE

Organization of the thesis

This work consists of two parts. The first part presents a general introduction with the main objectives of the research; the hypothesis on which the research theme was formulated; the original contributions of this research, not previously reported in the literature; a theoretical framework on the themes developed in the research; the main conclusions obtained from this work; suggestions for future works, which were determined on the basis of the deficiencies and difficulties from this work. Finally, is presented the works developed by the research group, which aim to know in detail the dynamic behavior of coffee plants during the harvest.

The second part consists of three scientific articles: a review article on the applications of the finite element method in three areas of agricultural engineering (Article 1); an article on the physical and mechanical properties determined in the laboratory (Article 2) and an article on the modal properties extracted from the numerical simulations (Article 3).

Article 1 represents a theoretical basis on the finite element method and its main applications related to this research. This method was used in the stage of obtaining the natural frequencies of the model previously developed, which were compared to the frequencies obtained in the laboratory for model validation.

However, to perform the simulations it is necessary to know the physical characteristics of the plants, such as elasticity modulus, specific mass and Poisson's ratio. These data serve as input to supply the simulation of the real physical system, allowing the extraction of natural frequencies and modes of vibration. Article 2 presents the data of physical characteristics, which were obtained in laboratory tests, for specimens formed from trunks and branches of samples of coffee plants.

Article 3 uses data obtained in the Article 2 and the theoretical basis to achieve the final objectives of this work, which are to evaluate the dynamic behavior of coffee plants and validate the model developed, thus finalizing the research.

1. INTRODUCTION

In the world scenario of coffee production, Brazil stands out as the main exporter. Among the coffee producing regions, Minas Gerais is the largest producer in quantity, in addition to producing the best quality coffee. The national coffee production contributes significantly to the agribusiness GDP and to the generation of jobs annually. The production chain of the crop has well-defined stages, in which the use of specialized labor is present since the preparation of the soil for planting until transporting the final product. Within the production chain, harvest and post-harvest stand out as the highest cost stages. With the scarcity of labor to carry out manual harvesting, the demand for mechanisms that perform the detachment and harvesting of fruits has increased, and it is common to find portable, assembled and / or self-propelled machines in the crops that assist producers in the harvesting stage.

The mechanized harvesting of coffee is carried out through the principle of mechanical vibrations, in which the mechanisms used transfer mechanical energy to the branches of the plants in order to promote the detachment of the fruits. Thus, knowledge of the physical and mechanical characteristics of coffee plants is extremely important, as these characteristics refer to the behavior of the product in different situations and at different levels of demand. And it is from the knowledge of these characteristics that it is possible to predict what will happen when the plant is requested by daily work factors, such as traction, torsion, cut and shear.

However, studies developed in order to understand the mechanical behavior of coffee plants are still incipient. Obtaining these properties requires time in the laboratory and availability of samples, as they are determined from destructive tests and must be determined for each part of the analyzed system.

Mathematical tools such as modeling and simulation can be used to assist the analysis of a vibratory system. Such tools consist of representing the important aspects of the real physical system, knowing its governing equations, solving them making it possible to interpret the results obtained. Among the numerical methods used in the analysis of static and dynamic systems, the finite element method (FEM) stands out, which is commonly used for the analysis of multi-physical problems and enables its application to the solution of mathematical models of physical systems through simulations with a high degree of reliability.

The knowledge of the mechanical characteristics of the coffee plants associated with representative models can provide accurate information that help in improving the efficiency of the crop harvest, either in the design phase of the harvesters or in adjustments made in the field. However, the mechanical characteristics in coffee culture are still poorly known and the models used are composed of geometric approximations, without taking into account the real deformations of the plants.

In this way, this work aims to analyze the dynamic behavior of coffee plants from numerical simulations performed on a previously developed dimensional geometric model. Therefore, the following specific objectives were established:

- Determine the physical and mechanical characteristics from specimens from the trunks and branches of coffee plants samples of the *Coffea arabica* variety, Catuaí Vermelho cultivar (IAC 144);
- Determine the modal properties of model (natural frequencies and vibrations modes) via numerical simulations using the Finite Element Method in a deterministic way;
- Analyze the dynamic behavior of the system subjected to mechanical vibrations;
- Validate numerical simulations using the model developed from results obtained from laboratory vibration tests, with samples of whole coffee plants.

2. HYPOTHESIS

Coffee harvest mechanization is a consolidated practice among the main producers, mainly in flat areas where the entry of harvesters is facilitated. The principle of mechanical vibrations is used by these machines to transmit mechanical energy to the branches of plants and to induce the detachment of their fruits.

The presence of fruits in unwanted ripeness, as well as impurities (sticks, stones and leaves), contributes negatively to the harvesting process. Furthermore, the quality of the harvested coffee interferes with its market value, so selective harvesting is a concept to be considered when mechanizing the crop harvest.

Predicting the behavior of plants in the field is a way to assist in decision making when using machines to harvest coffee fruits. Therefore, numerical simulations can be used to predict how the plant will react during the harvesting process. Knowing the natural frequencies that the plant experiences when interacting with the machines in the different stages of fruit ripening scenarios for selective harvests can also be evaluated. However, for the results to be the closest to the real behavior of coffee plants in the field, physical and mechanical characteristics of the plants must be determined and a representative model must be developed.

3. ORIGINAL CONTRIBUTIONS

This work can contribute for the coffee plants behavior understanding during harvesting of fruits considering the mechanized process. In this research, samples of the whole coffee plants were taken from the field and subjected to free vibration tests in the laboratory. From these tests, it was possible to extract the values of natural frequencies at different regions along the plants.

Specimens were produced from the trunks and branches of coffee plant samples, and submitted to compression and tensile tests, respectively, in a universal testing machine, to determine mechanical characteristics, taking into account the material anisotropy (woody).

The data obtained for elasticity modulus, Poisson's ratio and specific mass were used to simulate the dynamic behavior of plants, in free vibration. In the simulations, a geometric model, developed from reverse engineering, was used to extract the natural frequencies and vibration modes. The data extracted from the simulations were compared to laboratory data.

The data resulted from this research can allow validations for developing geometric models using dynamic scenario by means of reverse engineering. It was also considered the anisotropy of the woody material of coffee plants which represented an advance in determining the geometric and mechanical characteristics and properties of coffee wood. Finally, the use of free vibration in the laboratory represents an innovation and viability in vibration analysis involving coffee plants studies.

4. THEORETICAL REFERENCE

4.1. Coffee characterization

The coffee crop in Brazil is produced mainly by small and medium producers, contributes to the generation of jobs and has a share in the national and regional GDP.

Coffee plants are tree plants of the genus *Coffea* that has more than 100 species, with emphasis on *C. arabica* (Arabica) and *C. canephora* (Conillon) (DAVIS et al., 2006). Brazil is the world's largest coffee producer and exporter, having produced in 2019 more than 34 million bags of Arabica coffee and about 15 million bags of Conillon coffee (CONAB, 2019).

Arabica coffee originates in the tropical forests of Ethiopia, Kenya and Sudan, at altitudes of 1500 to 2800 meters. For their production, areas with altitudes ranging from 800 to 1300 meters are recommended. In these areas the average temperature varies between 18º C and 22º C (which are beneficial for the species), with little seasonal variation. Precipitation is well distributed, ranging from 1600 mm to 2000 mm, with dry seasons extending for three to four months, coinciding with the cooler period (CAMARGO 2010; FERNANDES et al., 2012).

It is noticed that the production in the Cerrado is much higher than the average of the other Brazilian regions, highlighting the cerrado areas of Minas Gerais, which together with the other areas of the state represent the largest coffee producer in Brazil, with production of approximately 24 million bags in 2019 (CONAB, 2019; FERNANDES et al., 2012).

The choice of variety and lineage must be made concurrently with the definition of spacing, handling and climatic conditions. The main cultivars of Arabica coffee planted are Catuaí Vermelho and Catuaí Amarelo, in warm regions, where the average monthly temperature is above 19º C all year round; Catuaí Vermelho and Catuaí Amarelo, Tupi, Acaiá, Topázio and Rubi, in regions of average climate, where two months of the year (usually June and July) have an average monthly temperature below 19º C; and Mundo Novo, Acaiá, Icatu Amarelo, Catuaí Vermelho and Catuaí Amarelo, in cold regions, where four months of the year (usually from May to August) have an average monthly temperature below 19º C (SANTINATO et al., 2008).

The coffee produced in the Cerrado has high quality, as the climatic conditions contribute to a favorable harvest, since it is carried out when the climate is drier, with low humidity, avoiding risks of fruit fermentation in the plant and / or in the post-harvest (FERNANDES et al., 2012).

Some climatic characteristics are favorable to the production of Arabica coffee. The concentration of rain in the summer and much less in the winter favors fruit ripening and harvesting. Milder temperatures in autumn and greater thermal amplitudes (differences between maximum and minimum) also favor slower maturation. A greater amount of sunstroke, during the autumn and winter months, fruit ripening and harvesting is beneficial, avoiding harmful fermentations to the quality of the drink. The low humidity of the air is also beneficial for obtaining a drink of superior quality, attributing to the drink low acidity and chocolate flavor (SANTINATO et al., 2008; MATIELLO et al., 2010).

The ideal ripeness, which gives the fruit mass a higher quality, and consequently a higher market value, is the fruit in the cherry stage. Traditionally, the fruit is detached in cloths, featuring a manual harvest. However, the mechanization of the crop has been growing annually, due to the scarcity of labor for manual harvesting. The total detachment of the fruits present in the plant can cause loss of quality of the coffee drink, if the fruits are not isolated in each stage of maturation, and the impurities of the harvest are not eliminated (OLIVEIRA et al. 2007; ORTEGA and JESUS, 2011; FERNANDES et al., 2012).

4.2. Mechanized coffee harvesting

Since the mid-1970s, research has been carried out in Brazil in order to develop coffee harvesters to replace traditional manual harvesting, making the country a pioneer in the use of mechanized harvesting for the crop (OMETTO, 1989). The scarcity of labor to carry out manual harvesting has been a determining factor that contributes to the increase in operating costs and increases the demand for mechanized harvesting (SCUDDER, 1982). Significant reductions in the costs of harvesting coffee fruits were observed for the use of harvesters and the transfer of machines in contrast to the cost of labor used in manual harvesting (SANTINATO et al., 2015; CUNHA et al., 2016).

Ometto (1989) describes the coffee harvester as a gantry-shaped machine that operates on top of the plants, equipped with vibrating rods that work on both sides of the coffee plants, releasing the fruits that are later collected by retractable shovels. A fan is attached to the system in order to remove impurities such as sticks and leaves. Still, according to Ometto (1989), the implementation of mechanized harvesting in coffee crops promotes a good quality of the harvested product, close to the quality of manual harvesting, without, however, causing significant damage to the plants; reduces harvest time and operating costs; releases the crop more quickly for a new agricultural year; in addition to facilitating the administration of the harvest stage. In Brazil, coffee harvesters showed up to 95% efficiency in detach the fruits from the plants, however with the presence of fruits in unwanted maturation (TONGUMPAI, 1993).

The use of portable harvesters for semi-mechanized harvesting also demonstrates a good alternative for reducing the demand for labor (MEJÍA et al., 2013). Several devices that promote the detachment of fruits have been tested in semi-mechanized harvest. Some of these equipments were developed in the form of rakes that simply detached the fruits of the branches by breaking their peduncles, others were provided with mini cylinders connected to a source of excitation that caused vibration in the branches and consequently the detachment of the fruits (ALEXANDRINO, 1985). The equipment currently used consists of rods handled manually, which have vibrating rods that can be mechanically or pneumatically activated.

Carvalho et al. (2000) developed and tested in the field a portable detacher prototype varying the length of the vibrating rods and the excitation frequencies used. The authors proved that the use of the developed prototype had an average capacity 2.2 greater than the capacity of manual harvesting, even though manual transfer was necessary. However, the prototype also caused greater defoliation in the plants.

The concept behind the development of these harvesters is based on mechanical vibrations, which consists of the transfer of kinetic energy to potential energy, and potential energy to kinetic energy (RAO, 2008). A vibrating system is a dynamic system, in which its input and output variables depend on time (ZHAN et al., 2015). Therefore, to promote the detachment of coffee fruits, the machines must transmit mechanical energy to the plant, or to part of it during the harvesting process.

Gomes et al. (2016) worked with the transmission of vibration in coffee branches and found that as the frequency of vibration of the rods of the harvester increases, the detachment efficiency increases, with fruits in the cherry maturation showing detachment efficiency higher than the green fruits. The presence of impacts on the fruits resulting from the rods of the harvester also showed greater efficiency than the operation without impacts.

Of the dynamic characteristics, in the coffee harvest the frequencies and vibration amplitudes in which the systems are submitted are highlighted (FERREIRA JUNIOR et al., 2016). Therefore, it is natural that such characteristics are the target of research that seeks to understand and improve the mechanized harvesting process in coffee plants.

Oliveira et al. (2007) worked with two strokes of the harvester in the same row of coffee, varying the frequency and operational speed of the harvester. First, the speed was set at 0.45 $m.s^{-1}$, and the frequency varied by 10.83 Hz; 12.50 Hz; 14.17 Hz and 15 Hz. Subsequently, the frequency was set at 16.67 Hz and the speed varied by 0.60 $m.s^{-1}$; 0.72 $m.s^{-1}$; 0.29 $m.s^{-1}$ and 0.45 $m.s^{-1}$. The authors observed that by increasing the frequency, the volume of coffee harvested and consequently the efficiency of harvesting, as well as the defoliation of plants, increased in the first pass of the harvester. In the second pass, the authors observed that by increasing the speed, the volume of coffee harvested decreased, and the presence of coffee on the ground increased, due to the shorter exposure time of the plants to the vibratory action of the harvester rods. However, this result can be justified by the fact that as it is a second pass, the plant had less fruit. The increase in speed also increased the volume of coffee dropped on the ground, however defoliation and the efficiency of detachment of the fruits were not related to the operational speed of the harvester.

Santinato et al. (2014) evaluated a coffee harvester operating at frequencies of 750 rpm and 950 rpm (12.5 Hz and 15.83 Hz), in two coffee crops of the *Coffea arabica* variety.

This study contributes to the understanding of how the machines relate to the plants in different seasons and different vibrations, as the results demonstrated that the use of the higher frequency of vibration in the low production season did not increase the harvest efficiency and caused an increase in the detachment of leaves, while in high season the increase in the frequency of vibration caused greater efficiency of harvest without increasing the damages caused to the plants.

Silva et al. (2015) worked on treatments with three levels of vibration (13.33 Hz; 15.00 Hz and 16.66 Hz). To analyze the efficiency of the harvest, they quantified the amount of fruits harvested. The experiment was carried out for 70 days during different stages of fruit ripening. This study reinforces the results found in the study mentioned above. The authors found that the increase in the vibration frequency of the harvester rods provides greater efficiency in harvesting the fruits and also attests that, as the fruit matures, more fruits are harvested, however the presence of green fruits also increases, which are fruits in unwanted ripeness. It is highlighted here that the differences observed in this work were for the highest frequency value used. The authors also note that this difference among frequencies, associated with the crop maturity index, can be used in a selective harvesting method with the objective of harvesting only the ripe fruits.

Ferreira Júnior et al. (2016) studied different settings for the coffee harvester and recommend the following settings to promote selective harvesting: 12 kgf (117.68 N) load on the brake of the oscillator cylinder, 12.5 Hz vibration, and rods of 0.60 m to 0.64 m in length; or 10 kgf (98.07 N) load on the brake of the oscillator cylinder, 15.8 Hz vibration, and 0.54 m long rods. It is noted that the frequencies observed here are close to the frequencies mentioned in the aforementioned works. However, this work presents more complete adjustments, with different characteristics linked to the principle of mechanical vibrations being the target of the work, which are also characteristics linked to the physical aspects of the construction of the harvesters, such as the brake of the oscillating cylinder and the length of the vibrating rods.

In addition to the relationship between frequency, amplitude, stem length and working speed, for to function properly, coffee harvesters must take into account the relationship between force of fruit detachment and fruit mass. According to Wang (1965), this relationship is important to develop selective harvesting strategies, and the optimum harvest point can be found by adjusting the force of fruit detachment and the frequency amplitude applied to the plants.

Ferraz et al. (2012) innovated by using a prototype of the dynamometer associated with techniques of precision agriculture and geostatistics to map coffee production and the force of fruit detachment in green and ripe ripening stages. The fruits in the green maturation showed detachment force between 4.92 N and 8.36 N, and the ripe fruits showed detachment force between 9.34 N and 10.96 N. These values reinforce that the fruit harvest can be carried out selectively, adding value to the final product and consequently increasing profits.

Silva et al. (2013) analyzed, based on variations in the vibration frequency of the rods and operational speed of the harvesters, the force of fruit detachment in the mature and green ripening stages. Observing that the green fruits showed greater detachment forces than the mature fruits, the detachment force was then considered an indicative factor of selective harvesting and was used as a criterion to start harvesting the fruits. The authors could also infer that the harvesting efficiency increases as the vibration frequency of the rods and the operational speed of the harvester also increases.

Santinato et al. (2016) developed and evaluated a mechanized harvester for harvesting coffee on slopes of up to 30%. For this, Santinato et al. (2016) worked at different vibration frequencies (600 rpm, 800 rpm and 1000 rpm (10 Hz, 13.33 Hz and 16.67 Hz)), operational speeds (800 and 1000 $m.h^{-1}$) and slopes (10, 15, 20, 25 and 30%). The results indicated that on lower slopes the use of reduced speeds minimizes the fall of coffee fruits on the ground. The variation in slope showed no difference in harvest efficiency. The increase in the vibration of the rods increased the efficiency of the harvest at the highest speed. Mechanized harvesting on slopes above 20% requires 21.6% more uptime and the harvester downtime can represent up to 29.18% of the total harvest time depending on the number of maneuvers.

4.3. Mechanical properties of coffee plants

The mechanical properties of the various materials found in nature are revealed when the material is subjected to the action of external stresses, and are obtained in the face of stresses and / or deformations, which are the internal response to external stresses. The purposes of determining the mechanical properties of a material are to characterize it, determine its applications and obtain information about the quality of the products (GARCIA et al., 2012).

Wood stands out for its peculiar formation, presenting different resistance characteristics in its different layers, and it is its mechanical characteristics that define its behavior when subjected to mechanical efforts. These characteristics can be influenced by its mass, its humidity, its dimensional variation, and the presence and amount of defects (GARCIA et al., 2012).

The principle of mechanical vibrations, used in the harvesting of coffee fruits, is closely linked to some mechanical properties of plants such as their stiffness and mass (RAO, 2008), which cause direct changes in the responses of the coffee plants when requested by different mechanisms. Therefore, knowing parameters that quantify these properties helps to predict the behavior of plants when requested externally. In this way, harvesters can be adjusted when working in contact with plants in the field, establishing an efficient plant-soil-machinery relationship.

Ciro et al. (1998) determined physical-mechanical properties for the coffee fruit-peduncle system, Colombia cultivar. Three maturation stages (green, cherry and ripe) were used to determine the geometric and mass properties of the material (mass; medium, largest and smallest diameter; specific mass of the fruits, length and diameter of the peduncles) that were later used to arrive to an average characteristic value. The moment of inertia was determined from the geometric properties obtained and using a CAD program. The peduncle elasticity was obtained from the tangent of the stress-strain curve. To measure the variables that make up the graph, the fruit-peduncle system was tested as an embedded beam in which blocks of different weights of steel were affixed at the free end and the deformations caused were measured with the aid of a multimeter. From the modulus of elasticity and the length of the peduncle, it was possible to obtain its rigidity.

The values obtained for the elasticity constant, stiffness modulus and moment of inertia increased with the evolution of fruit ripening. With the values found for the physical-mechanical properties, a mathematical model was implemented to study the system's response to the application of forced vibrations.

Tobón et al. (1999) studied the fruit-stalk system of plants of the cultivar Colombia red and yellow, at three different ages (2, 3 and 4 years) and three maturation stages (green, cherry and ripe). Each fruit had its characteristic diameter measured and from these the average diameter was reached, in addition the diameters and lengths of the peduncles and fruit masses were measured. The system stiffness was determined using linear regressions from the values of forces applied to the system and the observed deformations. The detachment force of the fruits and the torsion and bending moments were also measured. As previously mentioned, the force of detachment from the fruits proved to be an important parameter for mechanized harvesting of the fruits. A shorter peduncle length indicates difficulty in applying mechanized harvesting. The values of fruit dimensions, masses and moments of inertia were favorable to selective harvesting.

Rodríguez et al. (2006) determined properties of the fruit-peduncle system of coffee, Arabica variety, cultivar Catuaí. For this, they used the technique of digital image processing to measure the dimensions of fruits and peduncles. The measured dimensions were the average diameters and lengths of the fruits and peduncles in the green and ripe maturations. The moment of inertia was determined by modeling the fruits and peduncles in a CAD-3D program. To measure the elasticity modulus, the technique of digital images was also used. Photographs of the systems were taken before and after the application of a known external load and the deformations occurred in the peduncle were calculated. The Poisson's ratio was calculated in the same way. To determine the bending moment necessary for the fruit to detach, a moment transducer was developed and built. The values obtained for the mechanical properties of the fruit-peduncle system in this work also showed a tendency to increase with the evolution in fruit ripening.

Coelho et al. (2015) determined the physical, geometric and mechanical properties for the fruit-peduncle-branch system of coffee plants, Arabica variety, cultivar Catuaí Vermelho, in green and ripe maturation. To determine the dimensions, elasticity modulus, damping ratio and Poisson's ratio, the authors used the technique of digital image processing. The masses were measured on a scale and the volume determined using the Archimedes principle, which made it possible later to obtain the specific mass of each part of the system. The elasticity modulus of peduncles and branches was measured from the tangent of the curves of the stress-strain graph obtained from tensile, compression and flexion tests, and for fruits, compression tests were used. Corroborating with the results of the studies mentioned above, the geometry of the system tended to increase with the evolution of fruit ripening. The green fruits showed greater resistance to detachment than the ripe fruits. The system was characterized as undamped.

Carvalho et al. (2016) determined the physical properties of coffee trunks, Arabica variety, cultivar Catuaí Vermelho. The plant trunk samples were subjected to compression tests in a universal testing machine. The tests were photographed and the deformations obtained through the processing of digital images. The volume of the samples was determined by the Archimedes principle, and the specific mass of each sample was calculated with the volume and mass data. The properties found served as a basis to implement a mathematical model to study the static behavior of coffee plants. The authors verified that the model is dependent on the values of the mechanical properties of the plant and that these properties need to be better studied, taking into account the anisotropy of the wood.

The results obtained in these studies contribute to develop strategies for harvesting coffee fruits more efficiently.

4.4. Modal properties of coffee plants

When a system that is subject to mechanical vibration goes through resonance, it experiences high amplitudes of vibration. It is these amplitudes of vibration that allow the fruits to detach from the branches in a harvesting process by mechanical vibrations. Resonances occur when the excitation source works at one of the natural frequencies in this system. Dynamic characteristics of the vibration of any system are expressed in terms of their modal properties, which are composed of natural frequencies, damping factors and modes of vibration (CIRO, 2001). Natural frequencies are associated with maximum amplitudes of vibration, while the modes of vibration indicate the deformation pattern in which vibration occurs (RAO, 2008).

Displacement transducers, accelerometers and extensometers are tools generally used to measure modal properties, however the use of such tools is hampered by physical factors and mechanical limitations. And it is because of these limitations that more advanced techniques such as the use of digital images and numerical simulations are being used to predict the dynamic behavior of coffee plants (VILLIBOR et al., 2016).

Ciro (2001) used a simplified model of the coffee fruit-peduncle system to simulate its dynamic behavior during harvest. This model was simulated with one and two degrees of freedom. Despite being a very rustic simplification of the system, the model allowed to know the dynamic behavior for the first mode of vibration of the fruit-peduncle system. The natural frequencies showed high dependence in relation to the physical and mechanical properties of the system. The values of natural frequencies tended to fall with the evolution of fruit ripening. The results demonstrate a low degree of selectivity and detachment of the fruits, these parameters being dependent on amplitudes, time and frequencies.

The finite element method (FEM) is widely used because it allows the solution of mathematical models of physical systems with a high degree of reliability (SERGELIND, 1984), and its wide use is due to the fact that it can be applied to several areas of engineering (VELLOSO et al., 2018).

Tinoco et al. (2014) worked with a model of the coffee fruit-peduncle system, cultivar Colombia. To analyze the system, they used the finite element model, which allowed the authors, in addition to extracting the natural frequencies, to make a thorough evaluation of the vibration modes of the system. The geometry used was obtained from the digitization of the three main angles of the fruits. The simulation was carried out for the fruits at all stages of ripening. The model was validated based on the error between the experimental and simulated fruit volumes, which did not exceed 9%. The simulations allowed the authors to develop a numerical-experimental process for determining the elasticity modulus for fruits at different maturities. The experimental results showed a decrease in the value of the elasticity modulus with the evolution in fruit ripening. The authors also identified in the simulations, the presence of what they called “selective bands”, which are specific vibration bands for fruits with incomplete ripeness, however, these results have not been validated.

Santos et al. (2015) simulated the fruit-peduncle system of coffee, Arabica variety, Catuaí Vermelho and Mundo Novo cultivars, in green, cherry and ripe maturation. The authors were able to identify a difference of more than 40 Hz for natural frequencies in green and cherry maturation, for the counterphase vibration mode. Such a mode of vibration was identified as more efficient in promoting the detachment of fruits. This result could be obtained because in addition to the modal properties, the authors also worked with the analysis of stress distribution during the harvest. The MEF, therefore, allowed the complete characterization of the dynamic behavior of the system subjected to mechanical vibrations. The extracted natural frequencies showed a tendency to decrease with the evolution of fruit ripening.

Coelho et al. (2016) innovated by using the stochastic finite element technique to model the coffee fruit-peduncle-branch system. In addition to approaching the MEF in a new way, the authors implemented a more complete model, with the presence of bunches of up to three fruits along the branch. The new approach proposed by the authors works on the properties used as input for the simulations (elasticity modulus and specific mass). For this, the values of natural frequencies are being approximated to the real values with random changes around the mean values of the elasticity modulus and the specific mass, minimizing the errors found between simulated and experimental values. The authors concluded that the values of natural frequencies decrease with the evolution of fruit maturation and with the increase in the number of fruits in the branch. The natural frequency bands between green and ripe maturities overlapped, making it impossible to indicate a strategy for selective harvesting.

Tinoco and Peña (2018) performed an analysis of stresses in the unions between fruit and peduncle and between peduncle and branch, and used the MEF to identify the distribution of stresses in the studied interfaces. In this work, the authors indicate that the frequency range between 120 and 150 Hz, can be used for selective harvesting of ripe fruits, and the evolution in fruit ripeness influenced the decay of natural frequency values. However, as in previous works, the authors suggest that such results be verified in the field.

It should be noted that the works cited show the same behavior for fruit ripening: with their evolution, natural frequencies show a tendency to decrease. And all the works considered only aspects of the plants based on approximate models of the real physical systems. But in all cases the MEF was efficient in studying the dynamic behavior of the coffee plants.

Souza et al. (2018) presented an innovation when working with a model that interacted the coffee branch with a rod from the coffee harvester. The coffee branch and harvester rod models allowed the authors to understand how the stress distribution occurs in the two mechanisms when they are interacting. The acceleration values found in the simulations allowed the validation of the model in MEF. The values for von Mises stress found coincided with values indicated in the literature. However, as it deals with the interaction with a biological material (coffee branch), little known yet, the authors suggest that real values for the mechanical properties of the branches should be determined to improve the results.

The models used so far present approximations, and although they represent the real physical system, they can still be greatly improved. One way to obtain more representative models is to use scanners. According to Ponticelli and Suski (2010), a scanner uses laser beams to cover the desired object line by line, making it possible to describe the three-dimensional aspects of the object due to the depth captured by the modulation of the signal used.

Carvalho et al. (2016) brought this technology to the modeling of a coffee plant. The main objective of the work was to build a representative model of a coffee plant that could later be used to simulate the behavior of coffee plants in the harvesting process. The authors scanned separate parts of the trunk and then joined them in a CAD-3D program. The branches were built from approximations of the real physical system and incorporated into the model. To validate the developed model, the authors proceeded with an analysis of stress distribution in finite elements, which presented some discrepant values from those obtained experimentally, but which is ready for use in dynamic analysis of the behavior of coffee plants subjected to mechanical vibrations.

The knowledge of the physical and mechanical characteristics of the materials associated with a representative model of the real system can result in simulations that will return behaviors very close to the real ones, allowing the researcher to understand the dynamic behavior of the coffee plant at the time of harvest.

5. GENERAL CONCLUSIONS

This work was developed with the objective of understanding the dynamic behavior of coffee plants when subjected to mechanical vibrations during the harvesting process. To study this behavior, a geometric coffee model was subjected to numerical simulations, from which its modal properties were extracted, using the finite element method. To supply the simulations, geometric and physical characteristics of coffee plants were determined in the laboratory.

The methodologies used in the work made it possible to obtain the geometric, mechanical and modal characteristics and properties, in 20 samples of coffee plants, considering the anisotropy of the material.

The results obtained indicate the following values, for the properties and mechanical characteristics of specimens made from the trunks and branches of coffee plant samples:

Elasticity modulus of the trunks, determined from compression tests in a universal testing machine: 1090.94 MPa in the longitudinal direction and 108.60 MPa in the transverse direction.

Elasticity modulus of the branches, determined from tensile tests, in a universal testing machine, in the longitudinal direction: 507.72 MPa.

Poisson's ratio, determined by direct measurements: 0.25 for the trunk and 0.09 for the branches.

Specific mass: 1070.05 $kg.m^{-3}$ for the trunk and 1036.33 $kg.m^{-3}$ for the branches.

The model used allowed to simulate the dynamic behavior of plants, under mechanical vibrations. The natural frequencies obtained in laboratory tests were compared with the natural frequencies extracted from the simulations, and made it possible to validate the model previously developed from a coffee plant.

The frequencies found in the laboratory tests are concentrated between 10 Hz and 30 Hz.

The knowledge of the physical properties of coffee plants assists in making decisions for the construction, design and operation of machines that harvest coffee fruits using the principle of mechanical vibrations.

6. SUGGESTIONS FOR FUTURE WORKS

Some deficiencies of this work can be improved in the future, allowing studying a scenario with a greater representation of the real physical system. The specimens used, despite being made with rigor, do not yet represent a standardized form according to ABNT. The difficulty in being able to standardize the bodies of evidence comes from the excessive number of nodes present along the trunk of the coffee plant. The difficulty of using standardized specimens represents a limitation of this work.

Another limitation found was the difficulty in identifying the vibration modes, both in laboratory tests and in simulations. However, as we evaluated a free system in this work, this result was already expected. In this case, it is suggested to analyze the plants in a embed way, in the laboratory or in the field. In this way, more representative boundary conditions can be applied to the model in order to identify the vibration mode in both stages of the work.

7. WORKS DEVELOPED BY THE RESEARCH GROUP

This is the third work in a series of works carried out with the aim of thoroughly understanding the behavior of coffee plants during the harvesting process.

Carvalho et al. (2016) developed a geometric model of coffee, from the scanning of a real plant, obtaining a geometry that can be used to simulate various scenarios in which the plant is requested externally. In addition to the model, the authors worked on determining the physical properties of the trunks and branches, without, however, considering the anisotropy of the material.

The authors also performed static simulations in order to validate the developed model.

The results of this research represent an advance in the modeling of coffee plants, made until then with very robust geometric approaches.

Souza et al. (2018) used part of the model developed to study the behavior of coffee branches in interaction with the rods of the harvesters. In this work, the authors were able to evaluate the behavior of the branch under the direct impact of a harvester rod.

For this, the authors made dynamic simulations, extracting the modal properties of the branches and validating the results with the values obtained in laboratory tests.

Both works served as a basis for this research to be carried out. And, in turn, the results presented here increase this database, in order to provide a basis for future research that seeks to understand the dynamic behavior of coffee trees when subjected to mechanical vibrations.

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PART TWO – ARTICLES

ARTICLE 1:

The Finite Element Method Applied to Agricultural Engineering: A Review

Article written according to the Current Agriculture Research Journal, in which it was published in volume 6, of 2018 (pages 286-299).

ISSN: 2347-4688, Vol. 6, No.(3) 2018, pg. 286-299

Current Agriculture Research Journal

Journal Website: www.agriculturejournal.org

The Finite Element Method Applied to Agricultural Engineering: A Review

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Abstract

The use of numerical simulations has been widespread in many engineering fields and related areas. One of the main numerical methods used in modeling and simulations is the finite element method (FEM). Despite its wide dissemination, especially in mechanical and civil engineering, FEM has high potential to be applied in other areas, such as in agricultural engineering. This paper aims to present a review of the FEM applications in three agricultural engineering areas. This research is focused on agricultural mechanization, agricultural product processing and soil mechanics, since these are agricultural engineering areas with highest number of publications using FEM. As result, it is expected greater FEM dissemination in other agricultural engineering areas. In addition, modeling and simulation techniques can be widely used in order to represent the increasing behavior of agricultural machinery and products from real physical systems.

Article History

Received: 11 October 2018
Accepted: 6 November 2018

Keywords:

Agricultural Products;
FEM;
Modeling;
Numerical Simulation

Introduction

The increasing processing capacity in the development of computational resources has made the use of numerical simulations disseminate over the years in several engineering areas.[1] A model can be defined as a representation (approximation) of a real physical system through equations, usually differential ones, and can be described by a finite or infinite number of degrees of freedom, which characterize discrete or continuous problems, respectively. Numerical methods are used as alternatives to obtain approximate solutions to problems when an analytical solution cannot be developed.[2,3,4]

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Doi: http://dx.doi.org/10.12944/CARJ.6.3.08

Based on numerical procedures allied to computational resources, the solution of typical engineering problems can be obtained, except when the model discretization is very large, since the computer capability in these cases may be limited. Numerical methods involving geometric domain discretization is being proposed to solve problems that not show exact analytical solution from mathematical methods. The finite element method (FEM) is a numerical procedure for solving physical problems governed by differential equations. The origin of FEM cannot be accurately predicted since its basic principles date back more than 150 years; however, the first publications mentioning the FEM are from the mid-50s and a significant advance in its development occurred between the 1960s and 1970s.[5,6,7,8] This method is based on discretizing the domain region of the problem, formulating approximate equations, developing and solving these equation systems, and calculating the variables of interest.[2,4]

The FEM results in determining approximate values of desired parameters at specific points such as force, velocity, displacement and stress, called nodes, from linear or non-linear equation systems. A continuous approach function is assumed to represent the solution at each node. The approximate complete solution of the problem is defined by local interpolations in each element (set of nodes), which has continuity guaranteed by establishing previously a connectivity among the nodes. When the size of elements tends to zero and the number of nodes tends to infinity, then the exact solution is obtained.[3,4,9]

The equation of motion for systems with multiple degrees of freedom subjected to external requests is represented in Equation 1. The system characteristics are the input parameters of analysis, and are represented by mass, stiffness and damping matrices. The vector of external requests represents parameters that cause deformations. It is important to understand the role of these parameters and boundary conditions of the system in the FEM modeling.[8]

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = \{F\} \quad (1)$$

Where $\{F\}$ is the vector of external loads; $\{\ddot{x}\}$ is the acceleration vector; $[M]$ is the structural mass matrix; $\{\dot{x}\}$ is the velocity vector; $[C]$ is the damping matrix; $\{x\}$ is the displacement vector; and $[K]$ is the stiffness matrix.

Despite the use in engineering areas, such as in mechanical and civil engineering, the FEM is still not widely used in agricultural engineering applications. Comparatively, even though this sector is responsible for the world production of food, fiber and energy, the agricultural sector has applied little the computational modeling and simulation tools for the development of technological innovations. It is desirable that this production gives sustainably without affecting biomes, seeking natural preservation of resources. Increasing productivity is one of the alternatives to increase global supply, especially for the food sector. However, to improve the performance of production systems and increase productivity, it is necessary to develop systematically technological solutions transferred and absorbed by the several sectors from the agribusiness supply chain.[10]

According to the projections of the United Nations (UN) Food and Agriculture Organization (FAO),[11] an increase in the agricultural productivity around 60% is expected by 2050 to meet the global needs. In this context, agricultural sector should develop new technologies at all production stages in order to increase the productivity of already cultivated areas, however, without increasing environmental impacts.[10] FEM applications in agricultural engineering is highly relevant to the agricultural sector since it allows understanding and maximizing the production processes, which is one of the main concerns of the sector in order to meet world food demand without necessarily using new areas.

The present review shows some FEM applications in the main areas where the method is used as a solution in agricultural engineering. Articles were selected from a survey to emphasize the real use in agricultural engineering, besides presenting advantages and disadvantages, and some innovations and evolutions of the FEM.

FEM Applications in Agricultural Mechanization

One of the agricultural engineering areas that can be benefited from the increasing use of FEM is the agricultural mechanization through two strands. The first one is related to the modeling and simulation of agricultural machinery and implements in order to obtain reliable data on the structural and mechanical behavior of machinery, detect possible damages, maximize the production process and optimize designs of parts, machinery and equipment. The second is the modeling and simulation of the interaction between machinery and plants in order to predict the biological behavior of materials involved in the cultivation, harvesting, post-harvesting, drying, storage and other processes (Table 1).

The numerical simulations are able to allow studying the behavior of products without needing to create prototypes, thus assisting both in the manufacturing process and in monitoring the feasibility of use, detecting possible usage or material failures.

Oliveira *et al.*[13] modeled and simulated a mechanical joint composed of a tractor and a coffee harvester to measure the highest stress points in order to improve the equipment operation. The model that represents the coupling in the trawl is composed of connecting rod and lever and discretized by second-order tetrahedral elements. The lever model used 9,085 elements and 15,757 nodes, and the connecting rod used 8,472 elements and 14,715 nodes.

The input parameters were taken from the literature and obtained as responses the maximum values of the von Mises stress at the critical point of each piece, which was approximately 7.84e6 $N.m^{-2}$ for the connecting rod and $3.92.10^6$ $N.m^2$ for the lever. The use of von Mises stress allows the designer or operator to infer about the integrity of the mechanism through the theory of linear elasticity, which can reduce the amount of material used in its construction or aid in decision making regarding the maintenance of the mechanism. Results found from simulations showed an error of only 4.3% in relation to the experimental ones and the model allowed localizing likely failure regions.

The performance of a tractor's wheel at different inflation pressures was simulated by Inaba and

Table 1: Use of FEM in agricultural mechanization

Author	Year	Studied variable
Savary *et al.*[12]	2010	Dynamic behavior in an orange tree model.
Oliveira *et al.*[13]	2014	Connection between drawbar and coupling system of a coffee harvester.
Silva *et al.*[14]	2014	Stress concentration in a coffee harvester model.
Tinoco *et al.*[15]	2014	Dynamic behavior in a model of the coffee fruit-peduncle system.
Santos *et al.*[16]	2015	
Inaba and Hiroma[17]	2015	The performance of a tractor's wheel at different inflation pressures.
Coelho *et al.*[18]	2016	Dynamic behavior in a model of the coffee fruit-peduncle-branch system.
Fu *et al.*[19]	2016	Dynamic behavior in an sea buckthorn tree model.
Carvalho *et al.*[20]	2016	Stress concentration in a coffee model.
Hoshyarmanesh *et al.*[21]	2017	Dynamic behavior in an olive tree model.
Li *et al.*[22]	2017	Penetration resistance of a cutting tool model in soil with maize roots.
Ebrahimi *et al.*[23]	2018	Dynamic behavior in a model of a scarifier rod.
Silva *et al.*[24]	2018	Static and modal frequency simulations in a coffee harvester`s chassis
Souza *et al.*[25]	2018	Evaluation of the interaction between a harvester rod and a coffee branch based on finite element analysis

Hiroma.[17] In this study, the authors used an anisotropic elastic wheel model that included vertical and horizontal rigidities, in order to simplify the three-dimensional models normally used for two-dimensional analysis by using tire, and soil models and a model from the friction between the tire and the soil. In this case, the Coulomb friction law was used for the friction model. The model was discretized by rectangular elements and the mesh was refined in the points of contact between the ground and the tire. In the simulations, the wheel was rotated adapting displacement increments between the contact nodes. In order to validate the model, a structure representing a tractor wheel was used to obtain the results of traction force and torque in the axis that were later compared to the values of distributed normal stress obtained from the simulations. Results showed agreement around 89%, demonstrating that the model was able to simulate the tire behavior. Silva *et al.*[14] and Silva *et al.*[24] modeled the coffee harvester structure and performed static and dynamic analysis to verify concentration points of stresses and displacements for two situations: the machine working with aligned rear wheels and the machine working with misaligned rear wheels. The mesh used for the model discretization was formed by triangular prism elements with sizes between 1.2 mm and 47.0 mm, generating 35,121 nodes. The simulation input data was taken from the SolidWorks software database. The model with misaligned wheels showed displacement values around 11.9% lower than the model with the aligned ones. The maximum von Mises stresses for both situations were close, showing a difference of only 1.9%. This paper had no intention to show any dynamic effects of a coffee harvester machine and this can be considered a limitation of the presented work.

Li *et al.*[22] modeled soil resistance with maize roots to penetration of a cutting tool. The soil was modeled as elastic-plastic material and the maize roots were considered as lines with different diameters. Two cutting blades represented the tool, one with the straight edge (A) and the other with serrated edge (B). Two different speeds were considered in the simulations, which were then compared with experimental data. The elements used in the model discretization were taken from the Abaqus software database. In the model of blade A, the C3D8R element (eight-node hexahedron) was used, forming a mesh of 182 nodes and 79 elements; in the models of blade B and soil with maize roots, the C3D4 element (four-node tetrahedron) was used, in which the meshes consisted of 1,331 nodes and 4,285 elements, and 115,707 nodes and 66,193,810 elements, respectively. The agreement of the simulation results with the experimental results was above 87%. The authors considered the FEM as a convenient and reliable prediction tool in the analysis and development of the working capacity of the crop tool. The use of the Abaqus software and other software gives us an idea of the diversity of use of the FEM.

Fatigue study can be performed considering that evaluated structure works under periodic excitation as in the case of subsoils and scarifiers. Ebrahimi *et al.*[23] simulated a scarifier shank model from a modal analysis in order to predict the fatigue life of implement shank using the Wirsching-Light and Dirlik methods. To this end, the developed model was based on the geometric properties of samples. The subspace stochastic technique was chosen to be used, since it does not require known input variables. The model was discretized by tetrahedral elements and experimental vibration data were measured at four points of the shank with the equipment in use. The highest error found between experimental and simulated results was 5.6%, thus validating the use of the model.

The approach in which it is possible to obtain the behavior of biological materials using the FEM has been used in the agricultural mechanization area, mainly in cultures that use the principle of mechanical vibrations to promote the detachment of its fruits during the harvesting process. These types of studies date back to the mid-1970s and generally consider structures as elastic, homogeneous, and isotropic.[26]

Dynamic behavior of a coffee tree was simulated by Tinoco *et al.*[15], Santos *et al.*[16], Coelho *et al.*[18] and Souza *et al.*[25]. Authors used models from part of a plant, such as fruits, peduncles and branches, based on approximations made in specific software of computer aided design (CAD) in order to perform dynamic simulations. Coelho *et al.*[18] used a stochastic approach to determine the natural frequencies of the fruit-peduncle-branch system, using stochastic fields of the model input data (elasticity modulus and specific mass). However, Santos *et al.*[16] and Tinoco *et al.*[15] worked in a deterministic way to determine the natural frequencies of the fruit-peduncle system, using input data with from the average of the samples collected to determine the input data.

Tinoco *et al.*[15] worked on a model composed of peduncle, pedicel and fruit. The fruit and peduncle were discretized by meshes composed of tetrahedral elements, while the peduncle was discretized by a mesh composed of hexahedral elements. This difference between elements used occurs to obtain an improvement in the discretization of the model aiming at a better representation of the boundary conditions and a lower computational cost. The study of Santos *et al.*[16] used a standard unstructured mesh with 10,216 tetrahedral elements and 1,988 nodes. In the study of Coelho *et al.*[18], the mesh composition was made by ten-node tetrahedral elements. In all the three cases, it was noted that the natural frequency value decreased with the evolution of the maturation stage of fruits. This behavior is explained by the loss of rigidity of the product with the evolution of the maturation stage. The fundamental frequency values resulting from numerical simulations were close in the three studies[15,16,18], between 17 Hz and 20 Hz for mature fruits and between 18 Hz and 23 Hz for immature fruits.

System behavior analysis can also be performed by using static analysis, such as in Savary *et al.*[12]. Authors developed three models of orange tree and performed the simulations in a deterministic way in order to analyze the maximum and minimum deformations occurring when the plant is stressed at pre-established frequencies of 3 Hz and 3.83 Hz. Models were developed in SolidWorks commercial software and simulated ANSYS. Input variables were pre-determined in laboratory tests. Discretized meshes used three-dimensional tetrahedral elements. The model was able to represent 50% to 60% of the real physical system. However, authors emphasize that through a more complete model using wood anisotropic characteristics, simulation results can be improved.

Fu *et al.*[19] simulated the dynamic behavior of sea buckthorn in order to establish a database for the development of crop harvesting machines. In their study, authors used a model developed in Pro/ENGINEER software and simulations in ANSYS software. The experimental setup was performed from a randomly selected five years old tree. In the system simulations, modal analyzes were performed, extracting main natural frequencies and vibration modes. Harmonic response was also analyzed when the steady state of the system was subjected to an external load. For the branches model from the tree, it was assumed a circular cross section was and the diameters were obtained from direct measurements from experimental samples. However, some regions of the branches were considered thin and they were not shaped / measured.

Experimental sample were submitted to laboratory tests in order to determine main mechanical properties required as inputs for the simulations. The model discretization was performed by eight-nodes tetrahedral elements which resulted in a model with 424,552 elements and 107,843 nodes. The model was considered elastic, isotropic and identical and the Block Lanczos method was used in this study. In this case, first 20 natural frequencies were extracted and values between 6.6 Hz and 31.8 Hz were found. Each extracted mode represented a vibration in different parts of the tree, however authors noticed a tendency of lower frequencies act on the branches and higher frequencies act on the trunk. Harmonic analysis demonstrated that the vibration in the trunk is inefficient, while the lateral vibration to the branches proved to be most appropriate. In addition, the point of load application between 58 N and 78 N acts frequencies between 20 Hz and 30 Hz, which proved that fruits could be detached. This study demonstrates MEF efficiency in predicting behaviors and uses them as a basis for machine design. Authors suggested that new simulations relating the applied load to the geometry of the branches and application points can improve the understanding of the dynamic behavior of sea buckthorn and improve the harvesting efficiency.

Carvalho *et al.*[20] statically modeled and simulated a coffee plant in order to predict displacements and stress concentration regions. The model used in the experiments was developed using reverse engineering from the trunk scanning from a coffee plant. In the model discretization, the authors proceeded with mesh refinement tests, reaching

Table 2: FEM usage in agricultural product processing

Author	Year	Studied variable
Vagenas and Marinos-Kouris[27]	1991	Development of fruit and vegetable models.
Dintwa *et al.*[28]	2008	Dynamic behavior in apple models.
Ambaw *et al.*[29]	2011	Kinetics of gas diffusion/adsorption in apple models.
Celik *et al.*[30]	2011	Stress concentration in apple models.
Nilnont *et al.*[31]	2012	Drying in a two-dimensional model of parchment coffee grain.
Li *et al.*[32]	2013	Stress concentration in tomato models.
Abbaszadeh *et al.*[33]	2014	Modal analysis in watermelon models for maturation prediction.
Pieczywek and Zdunek[34]	2014	Determination of stress-strain curves in a 2D model of onions.
Ahmadi *et al.*[35]	2016	Dynamic behavior in apple models.
Yousefi *et al.*[36]	2016	
Celik[37]	2017	Dynamic behavior in pear models.
Salarikia *et al.*[38]	2017	

a mesh with ten-node tetrahedral elements of approximately 2 mm. The displacements observed in the simulations represented up to 80% of the shortest branches and up to 46% of the longest ones, being this difference explained by the stiffness of the material. The developed coffee model represents an advance for future static or dynamic simulations, both of coffee itself and simulations involving the plant interaction with machinery and implements used in the coffee harvest.

Hoshyarmanesh *et al.*[21] obtained olive tree simulations for the prediction study of dynamic behavior from the system. Important parameters were considered for the system simulation, such as wood anisotropy, dynamic behavior of temperature and water content, and a more representative three-dimensional model. Authors described that this kind of analysis was able to optimize the efficiency and productivity of mechanized harvest system. The model was developed based on geometric properties of tree samples and was discretized by standard three-dimensional tetrahedral solid elements. As boundary condition, an orbital load was applied in terms of pressure. Simulation results showed less than 5% difference among the experimental results, highlighting the relevance of the dynamic analysis to improve the fitting parameters of the harvesting process.

These studies show the versatility of FEM within the area of agricultural mechanization by using different software, models and elements to perform the simulations.

FEM Applications in Agricultural Product Processing

The knowledge of the physical properties of biological (agricultural) products is also of great industrial interest in applications in order to perform processing steps such as transportation, drying, separation and classification (Table 2).

With the aid of FEM, the determination of such properties has been made accurately since the mid-1970s, when Rumsey and Fridley39 used the method for viscoelastic contact analysis in horticultural crops.

Vagenas and Marinos-Kouris27 proposed general models to be used in drying simulations of fruits and vegetables.The authors presented a theoretical basis in FEM used in the simulation of models, pointing out the difficulties on its use, since agricultural products do not show a standard geometry. The proposed methodology was applied in currants, apricots, potatoes and carrots, being observed that the mesh refinement significantly improved the model response in relation to the real physical systems.

In the models used in currants and apricots, the authors used an ellipsoid shape with symmetric axes, which is not desirable in simulations because the boundary conditions of models may be asymmetric. In the ellipse center were used hexahedral elements while a combination between hexahedral elements and triangular prisms was used in the edges. Regarding the currant, 21 elements were used to represent the quarter section of the model in the xy direction, while this number was 30 elements for the apricot and a series of six elements were used to represent the length of both fruits in the z direction. Potatoes and carrots models were discretized, represented by prismatic elements with arbitrary shape. In xy cross section plane, 40 elements were used, considering three elements along the z-axis in order to represent the model thickness. In this way, the used mesh showed 126 elements in a total of 196 nodes for currants, 180 elements and 168 nodes for apricots, and also 204 elements and 276 nodes for potatoes and carrots.

The authors obtained satisfactory results with the models developed. In this study, the difficulty of representing agricultural products in numerical simulations is evident. However, FEM was considered adequate to predict the drying behavior for products of different shapes and sizes. The ability to represent is an advantage of the FEM.

The grain behavior during drying is a way of predicting drying kinetics, volumetric shrinkage and mechanical damages that can cause waste and fall in the market price of agricultural products. In this sense, the FEM is an important tool to predict grain behavior during drying, similarly as in the study of Nilnont *et al.*[31], which described the drying kinetics in a two-dimensional model of a parchment coffee grain through FEM. The model developed by the authors was validated by comparing the simulated with the experimental results obtained. A mesh composed of 210 symmetrical triangular elements with two-dimensional central axis was used to discretize the coffee grain model. The results obtained in the simulations showed from 85% to 92% similarity to the observed results for the real physical system.

It is also possible to simulate gas diffusion/adsorption in ovens, such as in the study of Ambaw *et al.*[29] in which the authors simulated a chamber model where the 1-methylcyclopropene (1-MCP) air diffusion was simulated first and then the 1MCP diffusion associated with irreversible adsorption in an apple was simulated. The developed model was a replica of the real physical system, consisting of an apple inside a chamber. A sphere with same volume of the apple fruit was used. Diffusion was also considered as unidirectional and the model was simplified for simulation from a three-dimensional structure to a unidirectional, going through a two-dimensional structure.

Discretization was performed by 40,000 rectangular elements and 7,694 nodes with 64,200 degrees of freedom for the 3D model; by 9,632 triangular elements and 4,865 nodes with 27,200 degrees of freedom for the 2D model; and by 768 straight segments and 769 nodes with 1,922 degrees of freedom for the 1D model.

The one-dimensional model was sufficient to describe the behavior of diffusion and adsorption coefficients in apple. The accuracy of the values was 99.7% and 97.6% for the simulated scenarios. The authors emphasize that the FEM model associated with the non-linear least squares regression can provide a tool with potential to estimate diffusion values and referred gas adsorption behavior using time series data.

The model used must always be able to represent the real physical system, but it is also concerned with the computational cost gain. In this case, authors highlighted the concern with the model, being this one of the advantages in the FEM, since for both three-dimensional and one-dimensional models it was possible to obtain satisfactory results.

Agricultural and food products at different maturation stages have different physical characteristics, which directly influence their dynamic characteristics. Thus, an innovative analysis was performed by Abbaszadeh *et al.*[33] when using the modal analysis of watermelon for prediction of its maturation stage. The model used in this study was developed from the geometric characteristics. 35 samples and discretized three-dimensional rectangular elements of 20 nodes with three degrees[37] of freedom were used. Simulated results showed agreement around 99.4% when compared to experimental data.

The development of numerical methods allows working the non-linearity of models and dynamic behavior efficiently, being possible to predict resistance to impacts and injuries in agricultural and food products, without the need for destructive tests, which aids to optimize the harvesting and post-processing, and the development of more suitable packaging and transportation systems. Through the FEM, scenarios that allow a better understanding of the product behavior when stressed externally can be simulated. Similar studies were already performed with pears[36, 37,38,] apples[28,29,35,] tomatoes[32] and onions.[34]

In the pear studies, the authors analyzed the behavior of fruits subjected to impacts of different heights (from 0.25 to 1.0 m) on different surfaces (steel, wood and rubber) and with different fall directions (between 0º and 90°). The elements used for the discretization of models were ten-node tetrahedrons with a maximum size of 3 mm. The choice of this element is justified by its high accuracy and good representativeness of the shape boundary. Celik37 used model discretization by using hexahedral elements. A mesh with 518,894 elements and 108,835 nodes was used for simulations. In Yousefi *et al.*[36] and Salarikia *et al.*[38], meshes were used with 8,866 nodes and 6,123 tetrahedral elements, and 38,917 nodes and 33,198 tetrahedral elements, respectively. In Celik[37], authors modeled the fruit from a surface scanning, which represents an evolution in obtaining the model, since the authors can guarantee a more realistic view of the deformation behavior in relation to the models generated by CAD software. In both studies, physical properties of pears were used as input parameters in the simulations. Salarikia *et al.*[38] did not validated experimental results, whereas other studies showed agreement of up to 99% between experimental and simulated results.

Similar analyses were performed with apples. In Dintwa *et al.*[28] and Ahmadi *et al.*,[35] half apple models were developed, since pendulum experiments that were used for validation in these studies use half apples. However, in the study of Celik *et al.*[30], the model was developed from the scanning of an apple, representing an evolution in obtaining the model. Tetrahedral elements were used for the discretization of the finite element model. In Celik *et al.*[30], the mesh consisted of 37,203 elements and 43,828 nodes, whereas in the study of Dintwa *et al.*28, a refinement was used for each part of the model (666 elements in the shell, 2610 elements in the cortex and 294 elements in the apple core).

One of the important issues in a FEM analysis is selecting the appropriate element size. Mesh density is used to control the model accuracy and a smaller element size produces results more accurately. The selection of the mesh together the best element type should be done by designers from pre-simulation procedures. In this case, model's solution time must be taken into account for each mesh structure. The mesh chosen should be the one that best represents the model with the lowest computational cost. The authors found that although there are limitations on the FEM usage, they agree that the use of numerical simulations associated with digital models are very useful tools in predicting the behavior of biological materials for non-destructive testing and may be economically beneficial to examine damages in agricultural products.

Li *et al.*[32] performed experiments using 3D models to predict stress concentration areas inside tomatoes. In this case, three models were used and the model discretization was performed considering two tetrahedral elements in ANSYS software database. The mesh used for the model discretization had 2 mm elements to represent the exocarp and mesocarp, and 1 mm to represent the locule gel tissue. In the first model, the mesh consisted of 19,402 elements and 29,256 nodes, in the second by 21,824 elements and 41,601 nodes, and in the third by 22,878 elements and 53,239 nodes. In this study, the authors state that the nonlinear multiscale finite element method was able to predict from 65% to 92% of the internal mechanical damage behavior of tomatoes under different loading conditions.

Table 3: FEM usage in soil mechanics

Author	Year	Studied variable
Nielsen et al.40	1986	Literature review for numerical methods that solve the Richards Equation.
Milly41	1988	
Leib and Jarrett42	2003	Prediction of pesticide dissemination in the soil using the LEWASTE model.
Poodt et al.43	2003	Simulation of the compressive strength of the soil subjected to sugarbeet harvester traffic.
Bunsri et al.44	2008	Use of the Galerkin method to solve a model that predicts the sodium chloride diffusion in the soil.
Xia45	2011	Soil compaction behavior and tire mobility.
Hemmat et al.46	2012	Resistance to soil compaction.
Cueto et al.47	2016	Modeling of soil pressure distribution under agricultural tire traffic.
Godinho and Soares Jr.48	2017	Use of the adaptive technique BEM-FEM in the simulation of the elastodynamic behavior of the soil.

Pieczywek and Zdunek[34] used the FEM to determine stress-strain curves of the onion epidermis in order to predict the behavior when subjected to traction using a 2D model. The model was discretized using an average of 34,879 first-order triangles that impart plasticity, stiffening, large stresses and large deformation capacities to the model. The thickness of the tissue sample was used as input parameter in the simulation. The model was able to simulate large stresses, with approximations of up to 74% and non-linear behaviors.

Considering these studies, it is possible to have an idea of how the modeling can influence directly in obtaining FEM results and the difficulty that exists in its representation when agricultural products were considered. The convergence of results is influenced directly by the chosen element, being that the more refined meshes (discrete geometric model in nodes and elements) represent the real systems, despite having a higher computational cost.

FEM applications in soil mechanics

The objective of soil modeling by the FEM is to predict scenarios where unknown variables such as the physical interactions occurring in wet and dry soils and the dispersion of solutes in the soil are involved, as well as the diffusion of pollutants and wastes. The knowledge of these variables is important to perform numerical simulations, since they directly influence seed germination and propagation, besides your contamination (Table 3).

A lot of methodologies based on FEM have been developed since the 1980s in order to simulate the movement of solutes in saturated and unsaturated soils, including FEMWATER[49], SUTRA[50], SEFTRAN[51] and HYDRUS in the versions 1D[52] and 2D[53].

In the 1980s, Nielsen *et al.*[40] and Milly[41] performed a review of the deterministic and stochastic mathematical methods that solve the Richards Equation, used to describe the basic processes of water flow and chemical transport in the unsaturated zone of soils. Nielsen *et al.*[40] pointed out that the use of the FEM for this type of approach demonstrates advantages in relation to the other techniques already used due to the ability to describe more precisely the thresholds of the irregular system in multidimensional simulations, besides including more easily the average non-homogeneous properties. The method leads to more stable and accurate solutions with computational resources more efficient. Milly[41] emphasized that the Richards equation is more accepted for water flow analysis and the stochastic technique can be applied to this equation for solving the natural soil heterogeneity. Milly[41] also showed that the control of a computational problem must be performed carefully on the mesh construction in the FEM, especially the care in the position of nodes in space and time.

Soil pesticide movement was also simulated by Leib and Jarrett[42] using a model simulated by the FEM in order to compare the predicted and measured concentration of pesticide in the soil during its effectiveness period. The model was evaluated and validated based on data from a field study in which the pesticide was applied to control cucumber beetles. The governing differential equations were also solved by the Galerkin method[2], considering the nonlinearities arising from the heat exchanges recurrent to the experiment. The model converged to the data observed experimentally, showing errors from 3% to 17%, being efficient to represent the pesticide movement in the soil.

Bunsri *et al.*[44] simulated the movement of sodium chloride as a tracer in the soil at 5 and 20 cm depths. For the model numerical solution, they used the Galerkin method[2]. The results obtained in the simulation represented from 80% to 93% the results observed experimentally, demonstrating capability to simulate all the marker transport conditions and to estimate effectively the dispersion coefficients.

Soil compaction caused by traffic from agricultural machinery can also be simulated by FEM. Poodt *et al.*[43] simulated the soil behavior when subjected to the sugar beet harvester tires and wheel loads. The soil mechanical properties were known and used as input parameters of simulations. As output parameters, the authors calculated the preconsolidation stress, the compression index and soil dilatancy, all as a function of depth. Sizes, pressures and loads were simulated on the most common tires used for harvesting. Several soil cohesion levels were used because this information was not available. Detection of Coulomb plasticity areas was also included. In the simulation results, no compaction was found at great depths. The authors highlighted the lack of practical methods for validation of these models and the need to perform a sensitivity analysis on the input parameters.

Similar analysis was performed by Cueto *et al.*[47], in which the authors simulated the soil compaction occurred by the passage of a tire at different loads, inflation pressures and in different soil moisture. The generated model represented a soil track with a tire and was simulated in the Abaqus software. The model discretization was made by the element C3D8R (eight-node hexahedron), available in the software database. The element size was between 1 mm and 2.5 mm, and the mesh was more refined in the contact between the ground and the tire, and less refined inasmuch as it moved away from the contact. This refinement type improved the computational efficiency. The simulation results allowed the authors suggesting the shape, magnitude, distribution and depth transmission of the stresses underwent by the dry and moist soils when subjected to the traffic of agricultural tires.

Xia[45] used the FEM to predict transient spatial density and tire deformation. The formulation was used to capture the change in configuration at the ground horizon in contact with the tire, which combined with the elastoplastic model can be used to calculate the transient spatial density due to tire compaction in the ground. The author presented an innovative characteristic of modeling the spatial density change, which is desirable for the study of geotechnics, both in agriculture and civil engineering. The developed numerical model proved to be a robust tool, which can be used to predict soil compaction behavior and tire mobility.

Hemmat *et al.*[46] studied soil compaction with a different approach than that presented by Xia[45], in which the authors used the FEM in simulations considering the viscoelasticity to represent the soil compression curves and to understand their behavior when subjected to static loads. The model used by the authors allowed simulating the compaction effort and predicting the soil physical properties, occurring similarity of 69% among the simulation and experimental results.

Although the results are close to the real ones, studies need to be done to improve these results. Development of models closer to real ones and knowledge of input data are of fundamental importance to this type of simulation.

Godinho and Soares Jr.[48] researched coupling technique from methodologies that lately was used in several studies. Godinho and Soares Jr.[48] used

FEM and BEM (boundary element method) jointly to simulate the elastodynamic interaction of the soil. Coupling of methods allowed independent discretization, which makes the equation systems generally better conditioned, providing improved solutions.

In this technique, one of the domains remains unchanged, being its matrices computed only once while the other undergoes an adaptive refinement of the model discretization inasmuch as the solution is evolved, thus making the solution more efficient. To couple both methods, it is necessary to impose the continuity and equilibrium standard equations on the common interface. The iterative process is based on the successive transfer among the coupled domains. In the present study, there are two types of iterations: displacements prescribed in BEM and stresses prescribed in FEM and vice versa. Adaptive refinement can be described in four stages: the current mesh solution is determined; error is estimated at nodal displacement times; this error is used to select a set of elements to be refined; and finally the selected elements are refined. The authors used the coupling technique to simulate four applications as follows: (i) introduction of a solid structure into an infinite solid medium (soil), (ii) opening a soft soil trench in a more rigid semi-infinity soil, (iii) a concrete wall interacting with the surrounding soil, and (iv) introduction of a three-dimensional solid into a homogeneous medium. In conclusion, the authors emphasize the advantage of using meshes and independent solutions using the best method for each part of the model and without increasing the computational cost.

In the studies presented here, it is clear the advantages of using FEM in agricultural engineering which is linked to the technology knowledge in this research field. In addition, a breakthrough is presented when using the FEM associated with other consolidated methods.

Final considerations and future perspectives

The present paper presented a review on the FEM usage in the main areas of agricultural sciences. The use of FEM has been well accepted in the areas of agricultural mechanization, agricultural product processing and soil mechanics.

Based on this review, it was possible to observe that, regarding the agricultural mechanization, the FEM is mainly used in the field of machine design and prediction of dynamic behavior in several structures and agricultural machinery. For processing of agricultural products, it was verified that the FEM could be used to obtain physical characteristics of products and prediction of the mechanical behavior when subjected to drying. Finally, in soil mechanics, it was observed that FEM could be used to predict the movement of solutes in soils, among other applications.

In order to expand the use of FEM in agricultural engineering, it is expected that further development of agricultural products will be performed and disseminated using this tool in order to obtain models that are closer to real physical systems, thus disseminating the FEM in other agricultural engineering areas. In addition, the Discrete Element Method (DEM) combined with finite element algorithms can also be employed in future agriculture researches.

Acknowledgments

The authors would like to thank the University of Lavras, Fundação de Amparo à Pesquisa do Estado de Minas Gerais (Fapemig), Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) and Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (Capes) for the financial support.

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ARTICLE 2:

Physical and Mechanical properties of the Wood of Coffee Trunks and Branches

Article written according to the journal Coffee Science, in which it was submitted and awaiting evaluation.

ABSTRACT

Knowledge of the physical and mechanical properties of coffee trees is essential to the development of mechanisms that perform the harvesting of their fruits by the principle of mechanical vibrations; however, these properties have yet to be determined in the laboratory. In this context, the present study aimed to determine the mechanical and physical properties of coffee trunks and branches through tensile and compression tests by means of a universal testing machine. Elasticity modulus, Poisson’s ratio, and specific mass were determined. The methodology allowed the studied properties and a database to be obtained, and they can be used as a basis for the development and operation of the mechanism used in the mechanical and semi mechanical harvesting of coffee fruits.

Index terms: Elasticity modulus, Poisson’s ratio, coffee tree.

1 INTRODUCTION

Brazil is the largest coffee exporter and the second-largest consumer of coffee in the world, second only to the United States (OIC 2019; ABIC 2017). Among the regions with the highest crop production, the state of Minas Gerais stands out and, in addition to being the main Brazilian producer of Arabica coffee, produces the highest-quality coffee (FJP 2018).

Knowledge about the physical and mechanical properties of agricultural products is essential to the development of harvesting and postharvesting mechanisms, which are considered the costliest stages of the coffee production chain. These properties refer to the behavior of the product in various situations and request levels. The combination of a particular mechanism and the agricultural product can be achieved only when one can predict what will happen when the product is affected by daily operational factors, such as heating, cooling, traction, torsion, cutting and shear (Costa et al. 2014).

Ciro (2001) and Coelho et al. (2015) determined geometric and mechanical properties related to the elasticity of the fruit-peduncle-branch system of the coffee tree, and Carvalho et al. (2016) used compression tests to determine the mechanical properties of the coffee trunk; these properties were used as input data to perform numerical simulations to predict the dynamic and static behavior of the coffee tree when subjected to external forces. Souza et al. (2018), Tinoco et al. (2014) and Santos et al. (2015) also used mechanical properties known as the base to simulate the dynamic behavior fruit-peduncle system of the coffee and coffee branch.

Tensile and compressive tests were also performed by Villar et al. (2017), Velloso et al. (2017) and Oliveira et al. (2018) with the objective of creating a database of geometric and mechanical properties for the macaw palm crop, which, similarly to coffee, is a crop in which fruit harvest can be performed by machines that use the mechanical vibration principle (Grupioni et al. 2018).

In crops such as coffee, where the harvesting of fruits is performed by mechanical vibration, kinetic energy is transmitted to the plant or a portion of it by electrical, pneumatic, hydraulic or mechanical power sources (Coelho et al. 2015). For these purposes, knowledge of the properties related to elasticity and rigidity is important because different scenarios for harvesting the fruits can be predicted from the mechanical properties of the trunk and branch wood, thus justifying new investigations in the area.

In this context, the present study aimed to determine the mechanical and physical properties of coffee trunks and branches, which can be used as a basis for the development and operation of machines that perform grain harvesting by the mechanical vibration principle.

2 MATERIAL AND METHODS

The specimens came from trunks and branches of 20 whole coffee trees, 6 years old, which had an average length of approximately 2 m and were of the *Coffea arabica* variety, Catuaí Vermelho cultivar (IAC 144).

Each plant was collected daily. Specimens prepared from the trunk and branches were tested on the same day as collection to prevent losses in their chemical composition and moisture, which could interfere with the mechanical properties. To maintain field characteristics, the specimens did not undergo any type of drying.

Thus, the specimens prepared from the trunk were composed of parts cut directly from the trunk where bark was removed, without the branches. Each specimen had an approximate length of 0.07 m, totaling 12 to 15 specimens per plant (Figure 1). The length of the specimens was determined from previous tests of different sizes.

Figure 1 - Specimens produced from the trunks of a coffee plant sample and which were subjected to compression tests in the universal testing machine, in parallel and perpendicular to the fibers.

Each specimen was identified according to the part of the trunk from which it was removed: lower, middle or upper thirds (Figure 2).

Figure 2 - Identification in each specimen produced from the trunks of the coffee plants, which were subjected to compression tests in a universal testing machine, where S refers to the upper third, M to the middle third and I to the lower third.

The specimens prepared from the branches were cut directly from the samples of coffee trees with an approximate length of 0.02 m, totaling six specimens per plant, and they did not undergo any treatment (Figure 3).

Figure 3 - Specimens produced from the branches of a coffee plant sample and subjected to tensile tests, in a universal testing machine, in the direction parallel to the fibers.

2.1 Physical and Geometric Properties

Each specimen had its mass determined in a 0.001 g precision scale, Marte brand, model AD500. Its diameters and lengths were determined with an MTX caliper, model 316119, with a 0.01 mm precision. The mean diameter was calculated from the average of six diameters measured at both ends and in the middle of each specimen (Table 1).

Table 1: Mean diameter values for coffee plant samples

	Mean diameters (m)			
Sample	**Trunks**	**δ**	**Branches**	**δ**
1	0.031	0.003	0.006	0.0008
2	0.032	0.004	0.005	0.0002
3	0.025	0.003	0.003	0.0009
4	0.030	0.003	0.006	0.0008
5	0.027	0.002	0.007	0.0001
6	0.026	0.003	0.006	0.0003
7	0.030	0.002	0.006	0.0008
8	0.021	0.004	0.006	0.0011
9	0.025	0.004	0.005	0.0007
10	0.022	0.003	0.004	0.0005
11	0.027	0.001	0.006	0.0004
12	0.024	0.002	0.005	0.0007
13	0.027	0.004	0.006	0.0007
14	0.020	0.001	0.005	0.0007
15	0.022	0.005	0.006	0.0010
16	0.026	0.005	0.005	0.0012
17	0.027	0.004	0.005	0.0007
18	0.025	0.003	0.006	0.0005
19	0.028	0.005	0.006	0.0009
20	0.029	0.003	0.006	0.0006

δ: Standard deviation.

The volume of the specimens made from the trunks was determined by immersion in water following the recommendations of NBR 7190 (ABNT 1997), whereas the volume of the specimens made from the branches was approximated by the volume of a cylinder obtained from the measurements of their diameters and lengths.

The conventional specific mass was obtained by the ratio between the mass of specimens and their volume (Table 2), according to the requirements of NBR 7190 (ABNT 1997).

Table 2: Mean mass and volume values for coffee plant samples

	Trunks				Branches			
Sample	**Mass (kg)**	**δ**	**Volume (m³)**	**δ**	**Mass (kg)**	**δ**	**Volume (m³)**	**δ**
1	0.057	0.008	$54.30e^{-6}$	$7.93e^{-6}$	0.007	0.002	$7.72e^{-6}$	$1.82e^{-6}$
2	0.066	0.016	$62.60e^{-6}$	$1.40e^{-5}$	0.004	0.002	$4.84e^{-6}$	$4.99e^{-7}$
3	0.038	0.007	$36.40e^{-6}$	$8.24e^{-6}$	0.002	0.001	$2.33e^{-6}$	$1.23e^{-6}$
4	0.055	0.013	$51.89e^{-6}$	$1.21e^{-5}$	0.006	0.001	$6.14e^{-6}$	$1.60e^{-6}$
5	0.044	0.008	$41.31e^{-6}$	$7.41e^{-6}$	0.007	0.002	$8.15e^{-6}$	$2.64e^{-6}$
6	0.041	0.008	$39.00e^{-6}$	$7.67e^{-6}$	0.005	0.001	$6.16e^{-6}$	$7.01e^{-7}$
7	0.059	0.011	$54.55e^{-6}$	$1.01e^{-5}$	0.007	0.001	$6.50e^{-6}$	$1.53e^{-6}$
8	0.029	0.011	$27.73e^{-6}$	$9.93e^{-6}$	0.008	0.003	$7.61e^{-6}$	$2.68e^{-6}$
9	0.037	0.012	$35.55e^{-6}$	$1.26e^{-5}$	0.004	0.001	$4.53e^{-6}$	$1.20e^{-6}$
10	0.032	0.006	$30.33e^{-6}$	$5.79e^{-6}$	0.003	0.001	$3.87e^{-6}$	$9.29e^{-7}$
11	0.045	0.005	$42.00e^{-6}$	$4.55e^{-6}$	0.007	0.001	$7.31e^{-6}$	$9.07e^{-7}$
12	0.035	0.008	$33.23e^{-6}$	$7.53e^{-6}$	0.005	0.001	$5.33e^{-6}$	$1.37e^{-6}$

13	0.046	0.014	$42.89e^{-6}$	$1.41e^{-5}$	0.007	0.001	$6.57e^{-6}$	$1.45e^{-6}$
14	0.024	0.005	$23.40e^{-6}$	$4.27e^{-6}$	0.004	0.001	$4.83e^{-6}$	$1.26e^{-6}$
15	0.029	0.012	$29.00e^{-6}$	$1.17e^{-5}$	0.006	0.002	$6.62e^{-6}$	$2.08e^{-6}$
16	0.043	0.014	$41.10e^{-6}$	$1.38e^{-5}$	0.006	0.002	$5.83e^{-6}$	$2.35e^{-6}$
17	0.048	0.015	$44.27e^{-6}$	$1.38e^{-5}$	0.006	0.002	$5.67e^{-6}$	$1.36e^{-6}$
18	0.043	0.013	$39.80e^{-6}$	$1.16e^{-5}$	0.008	0.000	$7.58e^{-6}$	$1.16e^{-6}$
19	0.052	0.18	$49.50e^{-6}$	$1.71e^{-5}$	0.006	0.002	$6.82e^{-6}$	$2.08e^{-6}$
20	0.054	0.014	$49.70e^{-6}$	$1.27e^{-5}$	0.006	0.002	$6.30e^{-6}$	$1.20e^{-6}$

δ: Standard deviation.

The specimens from the trunks were subjected to compression tests, and the specimens from the branches were subjected to tensile tests in a universal testing machine (Instron, model EMIC 23-20) equipped with a 20 kN load cell, whose elasticity modulus and Poisson's ratios were determined, following the flowchart shown in Figure 4.

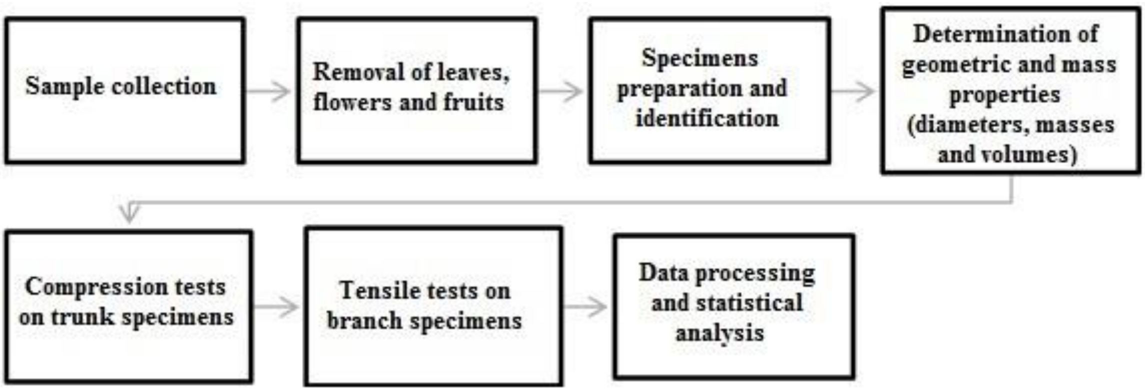

Figure 4 - Flowchart of the activities carried out in the field and in the laboratory, from the collection of the samples to the obtaining and analysis of the data extracted in the tests of traction and compression performed in a universal testing machine.

2.2 Elasticity Modulus

The elasticity modulus was determined by the slope of the secant line in the elastic region of the stress-strain curve (Garcia et al. 2012). The specimens made from coffee trunks underwent compression tests in two directions: parallel to the sample fibers (E) (Figure 5) and transverse to the sample fibers (E_D) (Figure 6).

Figure 5 - Specimen produced from the trunk of a coffee plant sample being subjected to compression testing, in a universal testing machine, in the direction parallel to the fibers.

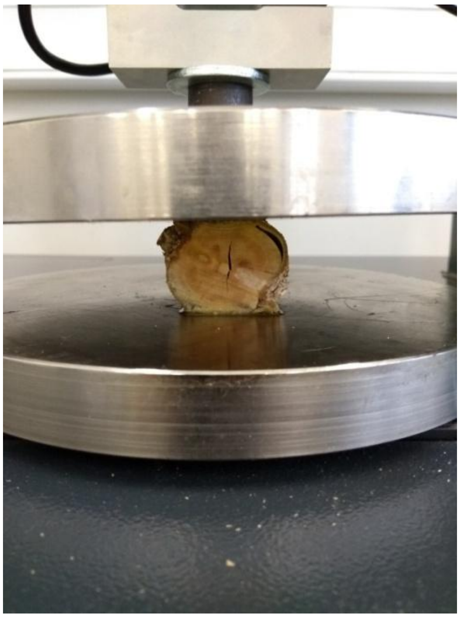

Figure 6 – Specimen produced from the stem of a coffee plant sample being subjected to compression testing, in a universal testing machine, in the transversal direction to the fibers.

The specimens made from the coffee branches were subjected to tensile tests in the direction parallel to the sample fibers (Figure 7).

Figure 7 - Specimen produced from the branch of a coffee plant sample being subjected to tensile testing, in a universal testing machine, in parallel direction to the fibers.

The routines to control both tests were programmed in the software application Bluehill. Each test had a speed of 0.01 m.min^{-1} and resulted in the values of time, stress and strain, according to NBR 7190 (ABNT 1997).

2.3 Poisson's Ratio

Poisson's ratio was determined by direct measurements in regions previously marked on the specimens (central region). The material of the specimens was considered isotropic, and the cross-sectional and longitudinal dimensions of the specimens were measured before and after the tensile and compression tests parallel to the fibers (Rao 2008). Variations in the dimensions allowed one to obtain Poisson's ratio (Equation 1) (Garcia et al. 2012).

$$\upsilon = -\frac{\varepsilon_T}{\varepsilon_L} \tag{1}$$

where,

υ = Poisson's ratio;

ε_T = cross-sectional variation, m;

ε_L = longitudinal variation, m.

A total of 48 valid tests were considered for specimens from the trunk, and 76 valid tests were considered for specimens from the branches. The values used were between zero and 0.5, and the outliers were excluded.

2.4 Statistical Analysis

The experiment was conducted in a completely randomized design with 20 samples and one replicate per sample. Each experimental unit consisted of a whole coffee tree.

The mechanical property data (elasticity modulus, Poisson's ratio and specific mass) were used to perform a descriptive statistical analysis of the data describing the means, standard deviations, maximum and minimum points, and coefficients of variation.

All the statistical analyses were conducted using the R programming (version 3.4.0) (R Core Team 2015).

3 RESULTS

The elasticity modulus was determined by the secant line method in compression and tensile tests (Figure 8).

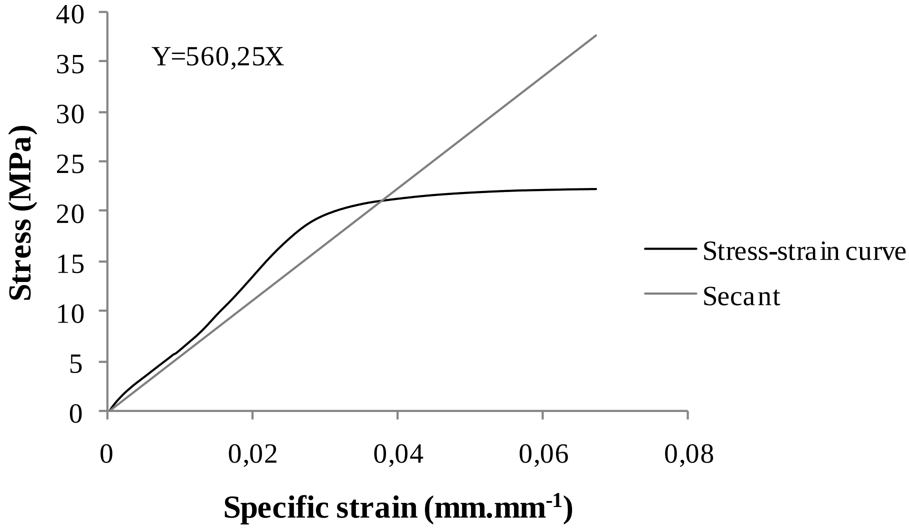

Figure 8 - Representation of the stress-strain curve and its secant, obtained experimentally for a specimen of the trunk of a coffee plant sample, submitted to a compression test, in the direction parallel to the fibers, in a universal testing machine.

The results found for the elasticity modulus for the specimens prepared from the coffee trunks and branches and tested in a universal testing machine are shown in Table 3.

Table 3: Values of the elasticity modulus in the longitudinal and cross-sectional directions, found for specimens of trunks and branches of coffee plant samples, which were subjected to compression and tensile tests in a universal testing machine

	Trunks		**Branches**
	$\mathbf{E_D}$	**E**	**E**
Mean (MPa)	108.60	1090.94	507.72
Standard Deviation (MPa)	50.73	347.00	147.80
Maximum (MPa)	452.35	1992.40	1798.20
Minimum (MPa)	19.10	428.52	57.20
Coefficient of Variation (%)	46.70	31.80	29.10

E: Longitudinal elasticity modulus; E_D: Cross-sectional elasticity modulus.

The values obtained for Poisson's ratio in this study are within the reference values for wood (Garcia et al. 2012) and for isotropic materials (Callister Junior 2007) (Table 4).

Table 4: Poisson's ratio values found for specimens of trunks and branches of coffee plant samples, which were submitted to compression and traction tests, in a universal testing

machine

	Trunks	Branches
Mean	0.25	0.09
Standard Deviation	0.11	0.06
Maximum	0.95	0.50
Minimum	0.02	0.01
Coefficient of Variation (%)	44.40	72.10

The specific mass values found in the present study are above the reference values (Garcia et al. 2012) for other woods used for structural purposes (Table 5).

Table 5: Specific mass values found for specimens of trunks and branches of coffee plant samples, which were calculated from the relationship between their masses and volumes

	Trunks	Branches
Mean (kg.m^{-3})	1070.05	1036.33
Standard Deviation (kg.m^{-3})	17.00	92.50
Maximum (kg.m^{-3})	1140.93	2144.97
Minimum (kg.m^{-3})	870.98	565.78
Coefficient of Variation (%)	1.59	8.93

4 DISCUSSION

Christoforo et al. (2013) note that the elasticity modulus is among the most important properties for dimensioning a structure. However, for materials such as wood, the determination of the elasticity modulus is compromised by the great anatomical complexity of the material and the variety that is characteristic of biological materials. In addition, wood has three axes of symmetry, which further complicates the determination of parameters related to its elasticity.

The values obtained for the elasticity modulus were lower than the reference values for woods used for structural purposes; for coniferous species, the values range between 3,500 MPa and 14,500 MPa, and for dicotyledonous species, the values range between 9,500 MPa and 24,500 MPa (Garcia et al. 2012). Stangerlin et al. (2008a) found 13,199 MPa and 16,944 MPa for wood from the juvenile and mature *Eucalyptus* genus, respectively. For juvenile and mature species of the *Pinus* genus, the values found were, respectively, 8,739 MPa and 17,866 MPa (Stangerlin et al. 2008a); 8,418 MPa and 13,376 MPa (Ballarine Nogueira 2005); and 10,894 MPa and 16,730 MPa (Ballarin and Palma 2003). Stangerlin et al. (2008b) found 10,897 MPa for juvenile species of the *Araucaria* genus, 14,367 MPa for mature plants of a species of the *Araucaria* genus, 13,570 MPa for juvenile plants of the *Patagonula* genus and 14,616 MPa for mature plants of the *Patagonula* genus.

Although juvenile wood presents elasticity modulus values lower than those of mature wood, these values are up to 20 times higher than those found in the present study.

The presence of imperfections in the wood may negatively affect its mechanical characteristics; the greater the number of imperfections, such as the presence of nodes, the lower the wood's capacity to withstand stresses. The wood of the coffee trunk in turn has an excessive number of nodes originating from branches inserted into the trunk (Garcia et al. 2012). Thus, coffee wood does not have the necessary characteristics to be used in a structural manner, and its use can be reversed for other purposes, such as for the production of charcoal (Leite et al. 2015).

Carvalho et al. (2016) found 2041.5 MPa (standard deviation of 326.1 MPa) for samples of coffee trunk of the Catuaí Vermelho variety, while Coelho et al. (2015) found an elasticity modulus of 1,940 MPa (standard deviation of 662 MPa) for specimens of coffee branches of the same variety. Both values are above those found in the present study. Differences that may eventually occur are explained by the variations according to age, climatic conditions and type of management to which the plants were subjected.

The elasticity modulus values can also be influenced by the compression direction during the test. For tests in the longitudinal and cross-sectional directions, respectively, Christoforo et al. (2013) found mean values of 12,003 MPa and 638.43 MPa for plants of the *Pinus* genus and mean values of 19,065 MPa and 897.86 MPa for plants of the *Corymbia* genus. This result shows the difference of values in the different directions, and the value found in the cross-sectional direction represents only approximately 5% of the value found in the longitudinal direction; i.e., the wood tends to withstand more longitudinal compression than cross-sectional compression.

Similar behavior was observed in the values found in this study, in which the cross-sectional elasticity modulus represents approximately 10% of the value of the longitudinal elasticity modulus, corroborating the results found by Ballarin and Nogueira (2003).

All coefficients of variation observed for the elasticity modulus can be considered very high (Pimentel Gomes 1987). In general, wood heterogeneity is high among plants, which may affect plants managed under the same management conditions and climate. It is therefore believed that this fact is due to chemical, physical and anatomical variations of the culture (Lobão et al. 2004).

The elasticity modulus and Poisson's ratio are mechanical properties related to the rigidity of the coffee tree structure; thus, variations in these properties can cause variations in the determination of their natural frequencies (Garcia et al. 2012).

Carvalho et al. (2016) found a Poisson's ratio value of 0.37 for specimens from the coffee trunk, and Coelho et al. (2015) found a value of 0.35 for samples of the coffee peduncle, both of the Catuaí Vermelho variety. Tinoco et al. (2014) found Poisson's ratio values of 0.34 for the coffee peduncle at the immature stage and 0.32 at the mature stage; the plants studied were from the Colombia variety. Ballarin and Nogueira (2003) found, for *Eucalyptus* plants, Poisson's ratio values between 0.013 and 0.70 for tests performed in different directions.

The interval of the Poisson's ratio is very limited, conferring magnitudes to the values found that are very close to the results found in the aforementioned studies.

This was the property with the highest values of coefficient of variation, which are higher than the values considered acceptable for agricultural products (Pimentel Gomes 1987). The conduction of the tests may have been the factor that influenced the increase in the coefficient of variation.

The specific mass, the elasticity modulus and the Poisson's ratio directly influence the natural frequency of the plant and show an inversely proportional relationship. In addition, numerical simulations are essential parameters for determining the modal properties of the plant (Rao 2008).

For *Eucalyptus* plants, Targa et al. (2005) found values of 1,003,000.00 kg.m^{-3}, 624.00 kg.m^{-3} and 877.00 kg.m^{-3} for the specific mass. Stangerlin et al. (2008a) found very similar values for the same species: 586.00 kg.m^{-3} for juvenile wood and 721.00 kg.m^{-3} for mature wood. For *Pinus* plants, Ballarin and Palma (2003) found 674.00 kg.m^{-3} for mature wood and 536.00 kg.m^{-3} for juvenile wood. Stangerlin et al. (2008a) found 499.00 kg.m^{-3} for juvenile wood and 671.00 kg.m^{-3} for mature wood. Stangerlin et al. (2008b) also found specific mass for the *Patagonula* species with values of 743.00 kg.m^{-3} and 721.00 kg.m^{-3} for juvenile and mature wood, respectively, and for the *Araucaria* species, they found specific mass values of 519.00 kg.m^{-3} and 524.00 kg.m^{-3} for juvenile and mature wood, respectively.

As for other properties, the specific mass of juvenile wood tends to be lower than that of mature wood. According to Garcia et al. (2012), woods with higher specific mass, in general, has better elastic properties. However, this property alone is insufficient to confer a structural character to the coffee wood.

Carvalho et al. (2016) found specific mass values of 607.00 kg.m^{-3} for coffee trunk samples of the Catuaí Vermelho variety. This value is lower than that found in this study; this variation may be due to the preparation of the specimens used in the two studies.

Coelho et al. (2015) found values of 900.00 kg.m^{-3} for the specific mass of coffee branches of the Catuaí Vermelho variety. For the same variety, Santos et al. (2015) found values of 1,200.00 kg.m^{-3}, 1,100.00 kg.m^{-3} and 1,090.00 kg.m^{-3} for fruits at different maturation stages. These values corroborate the results found in the present study.

Lobão et al. (2004) found in their study that specific mass is minimally related to the elasticity modulus of wood and, consequently, to its mechanical properties. For heavy wood, the authors found a specific mass equal to 880.00 kg.m^{-3}, which corresponds to an elasticity modulus of 19,479 MPa, and for light wood, they found a specific mass of 575.00 kg.m^{-3} and an elasticity modulus of 18,412 MPa; this establishes a relationship between the two properties. The authors also noted that lower specific mass indicate lower mechanical strength of wood, which is consistent with the results found in the present study, in which the specimens from the branches had lower specific mass than the specimens from the trunks.

According to Trendelenburg and Mayer-Wegelin (1956), in the case of wood, the specific mass variation is attributed to environmental and management factors, not only to the genus, and the coefficient of variation values can reach up to 30%. Thus, the values observed for the coefficient of variation of the specific mass in this study are within acceptable limits.

5 CONCLUSION

The method used in this study allows the determination of mechanical properties related to the elasticity of coffee trunks and branches. These properties help explain the dynamic behavior of the plant under different harvesting mechanisms.

The results obtained indicate the following values:

Elasticity modulus of the trunk, performed from compression tests: 1090.94 MPa in the longitudinal direction and 108.60 MPa in the cross-sectional direction.

Elasticity modulus of the branches, performed from tensile tests in the longitudinal direction: 507.72 MPa.

Poisson’s ratio, determined by direct measurements: 0.25 for the trunk and 0.09 for the branches.

Specific mass: 1070.05 kg.m^{-3} for the trunk and 1036.33 kg.m^{-3} for the branches.

The results provide a better understanding of the mechanical properties of the coffee tree. The determined properties, linked to representative geometric models, can validate experiments conducted in the field, assisting in predicting the dynamic behavior of coffee trees under different scenarios and under different loading conditions. Knowledge of the mechanical properties of coffee trees can assist in decision-making for the construction, design and operation of future machines that perform harvesting of coffee fruits by the mechanical vibration principle.

6 ACKNOWLEDGMENTS

The authors would like to thank the Fundação de Amparo à Pesquisa do Estado de Minas Gerais (Fapemig), Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) and Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (Capes), for financial support.

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ARTICLE 3:

Modal Properties of Coffee Plants via Numerical Simulation

Article written according to the journal Computers and Electronics in Agriculture, in which it was published in volume 175, of 2020 (electronic paper number 105552).

Computers and Electronics in Agriculture 175 (2020) 105552

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

journal homepage: www.elsevier.com/locate/compag

Original papers

Modal properties of coffee plants via numerical simulation

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ARTICLE INFO

Keywords:
Dynamic behavior
Natural frequencies
Coffee cultivation
Mechanized harvesting

ABSTRACT

Mechanized coffee harvesting is performed by machines that use the principle of mechanical vibration to detach the fruit. In this type of harvest, the machines transmit kinetic energy to the plant. Numerical simulations attached to representative models have been shown to be a viable tool for understanding the coffee harvesting process. In this sense, this study aimed to evaluate the dynamic behavior of coffee plants. For this purpose, a previously developed coffee plant model was used in numerical simulations to extract the modal properties and thus enable a better understanding of the dynamic behavior of coffee plants. The frequencies extracted from the simulations were validated with frequencies observed in laboratory tests. The frequencies found in the laboratory tests were concentrated between 10 Hz and 30 Hz. The validation of the model indicated that there is a correlation between the studied variables.

1. Introduction

The scarcity of manpower for harvesting coffee leads to the need to increase the efficiency of the equipment used in mechanical and semimechanical harvests to reduce operational costs because harvesting is one of the most expensive stages in the coffee production chain (Silva et al., 2014). According to Santinato et al. (2015), the use of harvesting machines at a certain speed and vibration level can cause severe damage to plants. Thus, it is important to study the aspects of harvesting that involve mechanical vibrations in the machines (Silva et al., 2014) and in the interactions with the plant (Souza et al., 2018).

Mechanized coffee harvesting is performed by machines that use the principle of mechanical vibration to detach the fruits. In this type of harvest, the machines transmit kinetic energy to the plant. For an efficient harvest with the lowest damage to plants, it is necessary to adjust the machines according to the parameters of frequency, amplitude and vibration time (Coelho et al., 2015).

A vibration system can be analyzed using mathematical modeling to represent the important aspects of the real physical system without making it excessively complex. The simulation process consists of obtaining the governing equations, solving the equations and interpreting the results. The equations that describe the vibration of the system are derived from the model previously created. The solutions of these equations result in the response of the vibration system, including the displacement, velocity and acceleration values of the various parts of the system (Segerlind, 1984; Rao, 2008). One of the numerical methods employed in the analysis of static and dynamic systems is the finite element method (FEM), which is commonly used in the analysis of engineering problems; this method can be used to solve mathematical models of physical systems through simulations with a significant degree of reliability (Marques et al., 2015).

The FEM is widely used because it can be applied to problems such as fluid mechanics, electromagnetism, heat transfer, electric fields and acoustics as well as classical problems in elastic-linear structural mechanics. In agricultural engineering, the FEM has been applied in several fields, such as agricultural mechanization, processing of agricultural products and soil mechanics (Velloso et al., 2018). More specifically, the FEM is commonly used for numerical simulations in coffee beans (Sachak-Patwa et al., 2019; Fadai et al., 2019).

Ciro (2001) performed modeling of the fruit-stem system of the Colombia coffee cultivar and considered scenarios with one and two degrees of freedom and different ripening stages. In that study, data on the geometry, mass, specific mass and elastic constant of the stem were used as inputs for the simulations, and the studied models were considered highly dependent on these parameters. In addition, it was ob-served that achieving a selective harvesting process by changing only the working frequencies of the machines would be difficult.

Tinoco (2017) and Tinoco and Peña (2017) performed simulations that considered representative models at each stage of fruit ripening. In Tinoco et al. (2014), each mode of vibration was analyzed for the first 20 natural frequencies, and at certain stresses concentrated at the fruit-stem interface, fruit detachment was facilitated.

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https://doi.org/10.1016/j.compag.2020.105552
Received 7 January 2020; Received in revised form 30 May 2020; Accepted 1 June 2020

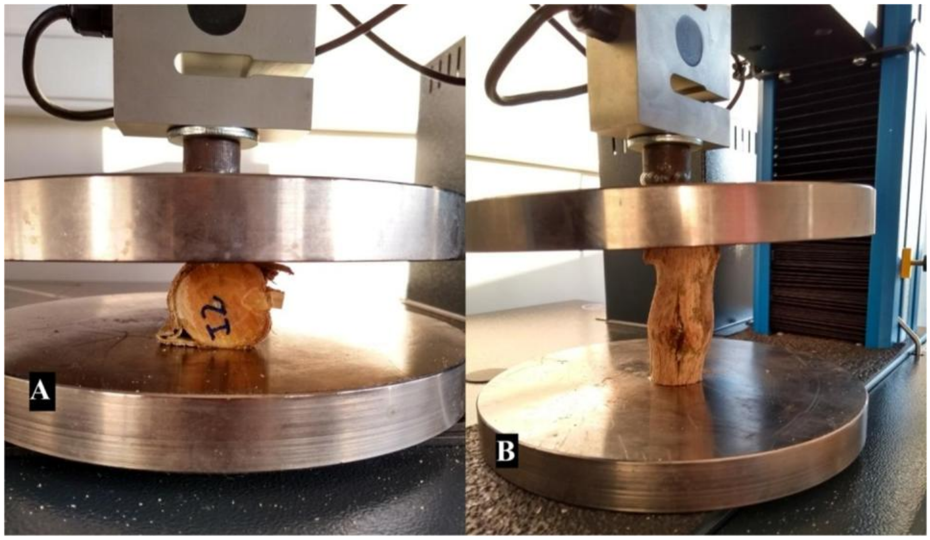

Fig. 1. Specimen submitted to the compression test in the direction perpendicular to the fibers (A) and parallel to the fibers (B).

Santos et al. (2015) studied the fruit-stem system of the Catuaí Vermelho and Mundo Novo cultivars and considered different stages of fruit ripening. The authors analyzed the pendular, torsional and counterphase vibration modes and found that the latter is the most indicated for harvesting because it has higher natural frequencies and can be used in selective harvesting processes.

Coelho et al. (2016) studied the fruit-stem-branch system of the Catuaí Vermelho coffee cultivar. In that study, models with one, two and three fruits were analyzed using stochastic finite element analysis. The overlaps of the frequencies found for the unripe and ripe ripening stages demonstrated that selective coffee harvesting by changing only the parameters related to vibration may not be viable.

Carvalho et al. (2016) studied the coffee plant to obtain a representative model of the real system using reverse engineering. For this purpose, parts of the trunk and branches of a whole plant were scanned to obtain a finite element model, which was validated by experimental tests that reproduced the simulations. The authors recommended that the mechanical properties of the coffee plant be better studied to improve the simulations using the same model developed.

Numerical simulations attached to representative models have been shown to be a viable tool for understanding the coffee harvesting process to support decision making based on accurate information. Further, these simulations obviate the need for field experiments. In this sense, the main objective of this study is to evaluate the dynamic behavior of coffee plants based on an in-depth study of the mechanical properties of coffee plants to determine the natural frequencies using numerical simulations.

2. Material and methods

To perform numerical simulations of the dynamic behavior of coffee plants, the geometric and physical properties of the system (the

Table 1
Mean values of the elasticity modulus, shear modulus and specific mass for the specimens from the branches and trunks of each sample coffee plants.

	Branches				Trunks					
		E	G	δ		E		G		δ
	n				n	L	T	L	T	
Sample 1	10	255.65	117.27	0.97	6	630.88	137.03	252.35	54.81	1.06
Sample 2	10	475.91	218.31	1.02	5	725.83	80.60	290.33	32.24	1.05
Sample 3	11	663.04	304.15	1.15	7	897.91	105.85	359.16	42.34	1.05
Sample 4	9	463.66	212.69	0.99	6	936.18	85.04	374.47	34.02	1.07
Sample 5	13	356.12	163.36	0.91	6	1051.41	93.40	420.56	37.36	1.07
Sample 6	11	380.92	174.73	0.97	6	1057.08	97.31	422.83	38.92	1.06
Sample 7	11	363.63	166.80	1.14	6	787.16	100.72	314.87	40.29	1.09
Sample 8	11	297.22	136.34	1.09	6	1101.48	103.93	440.59	41.57	2.20
Sample 9	11	617.40	283.21	0.89	6	1174.73	103.07	469.89	41.23	1.07
Sample 10	12	659.69	302.61	0.97	6	1139.61	111.31	455.84	44.52	1.06
Sample 11	12	556.16	255.12	1.05	6	1024.08	157.32	409.63	62.93	1.09
Sample 12	13	588.94	270.16	0.94	6	1181.35	114.34	472.54	45.74	1.06
Sample 13	9	454.55	208.51	1.08	6	1170.33	89.86	468.13	35.94	1.08
Sample 14	10	788.79	361.83	1.04	6	1693.60	167.40	677.44	66.96	1.06
Sample 15	10	765.39	351.09	1.01	6	1175.16	114.87	470.06	45.95	1.04
Sample 16	10	359.58	164.95	1.29	6	970.27	98.14	388.11	39.26	1.07
Sample 17	11	550.96	252.73	1.09	6	1124.54	113.44	449.82	45.37	1.09
Sample 18	10	468.35	214.84	1.11	6	1310.88	109.34	524.35	43.73	1.10
Sample 19	12	544.80	249.91	0.98	6	1362.92	84.51	545.17	33.80	1.06
Sample 20	10	543.64	249.37	1.04	6	1340.95	104.57	536.38	41.83	1.10

Legend: n = number of specimens; E = elasticity modulus; G = shear modulus; δ = specific mass; T = transversal; L = longitudinal.

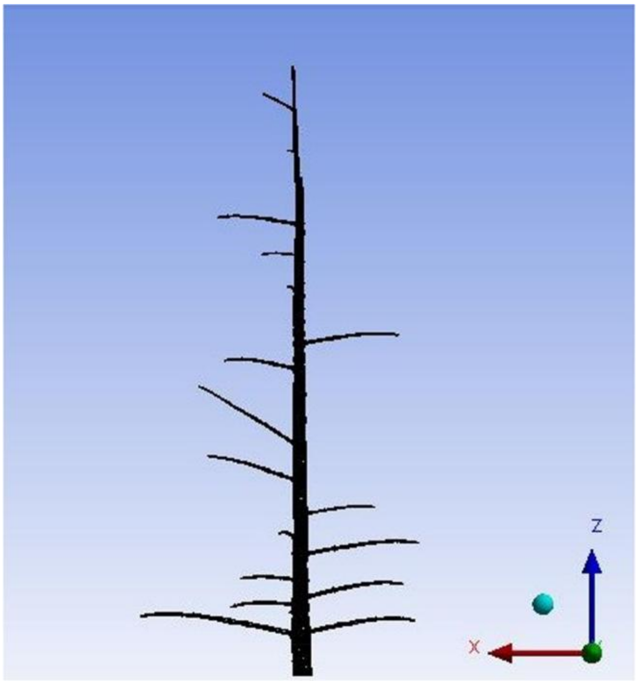

Fig. 2. Model used in the simulations.

elasticity modulus, shear modulus, Poisson's ratio and specific mass) were used as input parameters. Specific tests were performed to determine each property of the coffee wood.

The elasticity modulus, Poisson's ratio and specific mass data were determined in the laboratory using specimens from the trunks and branches of 20 samples of coffee plants, variety *Coffea arabica*, cultivar Catuaí Vermelho (IAC 144). The specimens from the trunks were subjected to compression tests, and the specimens from the branches were subjected to tensile tests. The specimens from the trunks were positioned at two different angles (perpendicular to the fibers and parallel to the fibers), considering the anisotropy of the material. And the specimens of the branches were positioned perpendicular to the fibers (Fig. 1).

In these tests, direct measurements were taken in the specimens to determine the elasticity modulus and Poisson's ratio. The specific mass was calculated from the difference between the mass and the volume of the specimens. To obtain the volume, the specimens were immersed in water.

The shear modulus was calculated from the Poisson's ratio and the elasticity modulus according to Eq. (1) (Garcia et al., 2012).

$$G = \left(\frac{E}{\upsilon + 1}\right) - 1 \tag{1}$$

where,

G = shear modulus, MPa;
E = elastic modulus, MPa;
υ = Poisson's ratio.

For the simulations, the anisotropy of the material was taken into consideration. Thus, the specimens from the trunks were considered orthotropic, and the specimens from the branches were considered isotropic. The collected values are shown in Table 1.

The Poisson's ratio values, obtained from laboratory tests based on the difference between the elongation and the necking of the specimens, were 0.09 and 0.25 for the branches and trunks, respectively.

The three-dimensional model was developed by Carvalho et al. (2016) (Fig. 2). This model consists of a plant with a trunk with a height of 2.15 m and an average diameter of 3.55 cm and branches with an average length of 31.62 cm and an average diameter of 6.39 mm.

Using this model, the commercial software ANSYS, version 14.5, was used to perform finite element analysis and extract the modal properties of the system. This platform allowed the discretization of the system (from the generation of unstructured meshes for three-dimensional domains), the formulation of equations and solutions and the subsequent analysis of the numerical results (from graphs, diagrams and animations). Thus, the model enabled the dynamic response of coffee plants to mechanical vibrations to be studied.

The mesh was selected based on a pre-simulation in which the number of elements was considered, making it possible to choose a mesh that represented the real physical system with the lowest computational cost. For a more refined mesh containing 378,285 elements, a solution time of 2,925 s was observed, while for a mesh containing 216,578 elements, the solution time was approximately 146 s. The

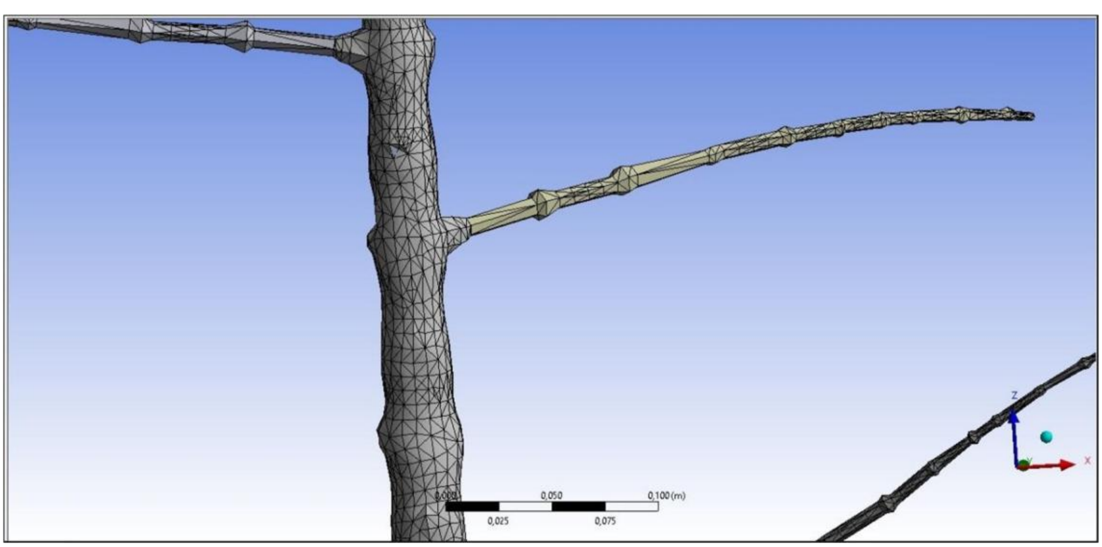

Fig. 3. Finite element mesh details.

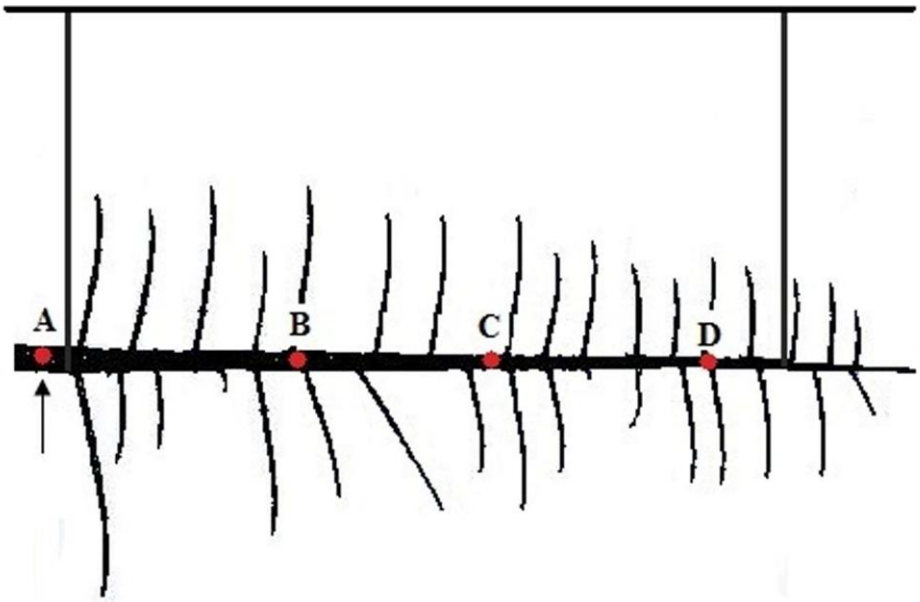

Fig. 4. Diagram of the whole coffee plant, bisupported at the ends, with the accelerometer reading points (A, B, C and D) and the point of impact of the hammer (arrow).

difference in the value of the observed frequencies was 0.19%. Thus, the mesh with 216,578 elements was used, as the models converged to a very close value with a reduction of approximately 2,000% in the convergence time. Therefore, the discretization of the model was performed using 10-node tetrahedral elements (SOLID187), with a size of 5.0 mm and a total of 216,578 elements and 395,889 nodes. Mesh details is presented in the Fig. 3.

The natural frequencies (eigenvalues) and the respective vibration modes (eigenvectors) were obtained from the formulation and solution of the eigenvalue and eigenvector problems.

2.1. The eigenvalue and eigenvector problems

To model undamped free vibration, system with multiple degrees of freedom were considered, as represented by systems of differential equations, which can be expressed in matrix form according to Eq. (2).

$$\begin{bmatrix} m_{11} & m_{12} & \cdots & m_{1n} \\ m_{21} & m_{22} & \cdots & m_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ m_{n1} & m_{n2} & \cdots & m_{nn} \end{bmatrix} \begin{Bmatrix} \ddot{\upsilon}_{11} \\ \ddot{\upsilon}_{21} \\ \vdots \\ \ddot{\upsilon}_{nn} \end{Bmatrix} \begin{bmatrix} k_{11} & k_{12} & \cdots & k_{1n} \\ k_{21} & k_{22} & \cdots & k_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ k_{n1} & k_{n2} & \ldots & k_{nn} \end{bmatrix} \begin{Bmatrix} v_{11} \\ v_{22} \\ \vdots \\ v_{nn} \end{Bmatrix} \begin{Bmatrix} 0 \\ 0 \\ \vdots \\ 0 \end{Bmatrix} \quad (2)$$

where,

m = mass, kg;
$\ddot{\upsilon}$ = acceleration, m.s^{-2};
k = stiffness, N.m^{-1};
v = displacement, m.

In three-dimensional finite element models the nodal displacements of a given element are represented by:

$$\{\upsilon\} = \begin{Bmatrix} u\ (x,\ y,\ z\ ) \\ v\ (x,\ y,\ z\ ) \\ w\ (x,\ y,\ z\ ) \end{Bmatrix}$$

where *u*, *v* and *w* are nodal displacements.

The eigenvalues can be determined assuming that the free vibrations are harmonic. The Eq. (3) enables the natural frequencies (eigenvalues) and vibration modes (eigenvectors) to be determined.

$$-\omega^2\ [M] + [K]\ \{\varphi_i\} = \{0\} \quad (3)$$

where,
$\{\varphi_i\}$ = the eigenvector associated with the i-th natural frequency of the system;
ω^2 = angular frequency, rad.s^{-1};
M = mass matrix, kg;
K = stiffness matrix, N.m^{-1}.

Thus, by equating the determinant of the matrix ($-\omega^2$ [M] + [K]) to zero, the natural frequencies of the system can be obtained (Hoffman, 1992; Reddy, 1993; Boyce and Diprima, 2002; Zienkiewicz et al., 2005).

For the calculation of the eigenvalues and eigenvectors, the numerical method of Block Lanczos was used, which is applicable to several engineering problems when there is a combination of solid elements; this method allows the extraction of a high number of vibration modes, with a fast convergence rate and a small memory requirement (ANSYS Inc., 1996).

The Block Lanczos algorithm is a classic variation of the Lanczos algorithm, in which the recursions of the model are developed using a block of vectors instead of a simple vector. This method employs an automated shift strategy combined with Sturm sequence checks to extract the number of requested eigenvalues (ANSYS Inc., 1996).

2.2. Validation of the finite element model

The three-dimensional model developed and implemented was validated against the frequencies observed during laboratory tests. As field experimentation is not feasible, a free vibration was used to determine the natural frequencies and provides support for forced

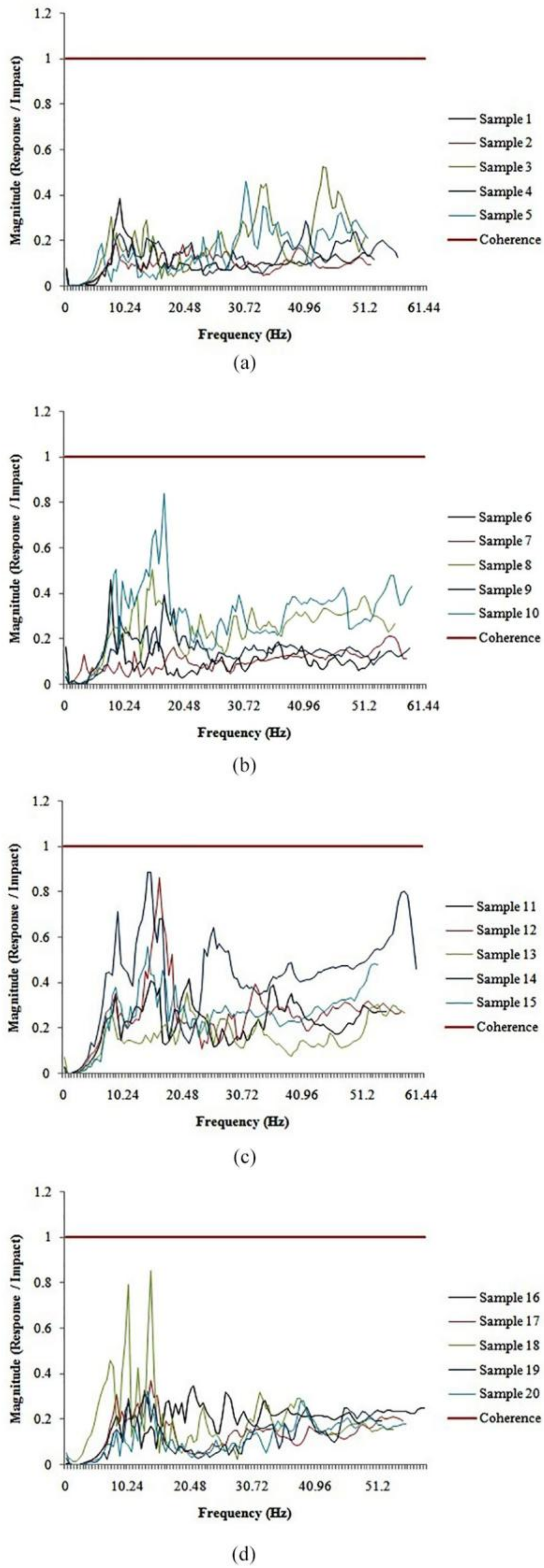

Fig. 5. (a). Representation of the amplitude of vibration in the frequency do-main for coffee plant samples 1, 2, 3, 4, and 5. (b). Representation of the amplitude of vibration in the frequency domain for coffee plant samples 6, 7, 8, 9 and 10. (c). Representation of the amplitude of vibration in the frequency do-main for coffee plant samples 11, 12, 13, 14, and 15. (d). Representation of the amplitude of vibration in the frequency domain for coffee plant samples 16, 17, 18, 19, and 20.

vibration analysis of a defined system. For these tests, a free vibration system was used in which the samples of whole coffee plants were bi-supported by a metal structure built into the laboratory ceiling. To fix the base and the end of the sample, two metal hooks were used, and the samples were raised using string so that they were not touching the ground. A forced vibration in the plant structure was performed using an impact hammer that applies loads to a certain point in the plant and had its vibration captured using highly sensitive accelerometers. The source of the excitation of the impact was always applied at the same point (arrow), and the readings with the accelerometer were made at four equidistant points (A, B, C and D) along the trunk of the sample (Fig. 4).

In the tests, the samples were subjected to vibration using an impact hammer (PCB Piezotronics brand, model 086C03) with a rubber tip and a sensitivity of 2.302 mV/N. The acceleration amplitudes were measured using a high-sensitivity accelerometer (PCB Piezotronics brand, model 352C33, 99.5/g (Eu)). The locations where the accelerometer was installed were scraped with a band saw until the inert material of the trunk bark was completely removed to avoid a damping effect on the reading of the plant vibration by the accelerometer.

A routine was developed for the acquisition of frequency data in the LabView software (National Instruments, 1998). This routine managed a data acquisition system (model NI cDAQ-9174) with four channels, which was used to read the accelerometer and impact hammer measurements and which returned the acceleration amplitudes and coherence values.

The convergence analysis of the results obtained for the model was performed using linear regressions and correlation tests. For this purpose, each simulated frequency result was compared to the natural frequency obtained for the respective sample in the laboratory tests. In the regression, the coefficient of determination (adjusted R^2) and the slope coefficient values of the fitted line were analyzed.

The correlation between the simulated and experimental values was assessed using the Spearman correlation test. Statistical analyses were performed using R, version 3.4.0 (R Core Team, 2017).

3. Results and discussion

The experimental natural frequencies obtained in the laboratory at one of the accelerometer reading points were identified in frequency spectra based on the amplification of the amplitude of vibration when the sample was subjected to impacts under free vibration (Fig. 5(a) to 5 (d)).

The coherence value is directly related to the laboratory tests and indicates whether there are noises between the impact hammer and the accelerometer signals. From this value we can infer about the quality of the test performed.

In all cases, the coherence equaled 1, which indicates that the response signals between the impact hammer and the accelerometer were linearly correlated, with no presence of interference or noise (Adam and Jalil, 2017).

Additionally, the highest incidence of frequency peaks was concentrated between 10 Hz and 30 Hz. Table 2 shows the frequency values extracted for each peak that was found.

The results in Table 2 corroborate the results of Coelho et al. (2016), in which the natural frequency values obtained for the first three vibration modes were between 10 Hz and 30 Hz for the coffee fruit-stem-branch system in the unripe and ripe ripening stages in Catuaí Vermelho cultivar coffee plants.

Santos et al. (2015) found values between 19.9 Hz and 23.3 Hz for the coffee fruit-stem system in the unripe, half-ripe and ripe ripening stages in a study that also used plants of the Catuaí Vermelho cultivar.

Tinoco et al. (2014) found values between 16.33 Hz and 19.38 Hz for the first two vibration modes of the coffee fruit-stem system in the unripe, semi-ripe, ripe and overripe stages for coffee plants of the Colombia cultivar.

Table 2
Natural frequency values obtained from the frequency spectrum for each coffee plant sample tested in the laboratory.

Natural Frequencies (Hz)																			
P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16	P17	P18	P19	P20
9.22	8.70	7.68	9.22	6.14	7.68	3.07	8.19	7.68	8.70	8.70	8.70	8.19	9.22	7.17	8.19	8.19	8.70	6.14	8.19
14.85	16.38	11.78	11.26	9.73	9.73	4.61	10.24	9.22	9.73	10.24	16.38	13.82	14.34	8.70	10.24	9.22	13.31	8.19	9.22
19.46	19.97	13.82	13.82	11.78	10.75	5.63	12.29	13.82	11.26	12.29	18.43	15.36	16.90	11.26	11.26	11.78	15.36	10.24	11.26
25.60	27.14	14.85	21.50	13.31	12.80	7.17	14.85	15.36	13.82	14.85	25.09	17.41	19.46	14.34	13.82	12.80	17.41	12.80	13.31
46.08	39.94	19.46	28.67	16.90	14.34	9.22	16.90	16.90	15.36	16.38	28.16	18.43	25.60	16.90	16.90	13.82	18.94	14.34	15.36
50.69	50.18	26.62	37.89	18.43	15.36	11.78	21.50	18.43	16.90	21.50	32.77	20.99	38.40	18.94	17.92	14.85	23.55	18.43	17.41
		30.21	40.96	21.50	18.94	14.34	23.04	19.97	19.46	27.14	38.40	24.58	58.37	20.48	18.94	16.38	33.28	20.48	18.94
		34.30	49.66	23.55	23.55	18.43	25.09	22.53	22.53	30.72	47.62	27.14		22.02	20.99	24.06	38.91	23.04	24.58
		44.03	54.27	26.11	25.09	20.48	28.67	26.11	26.62	33.28	52.22	33.28		23.55	22.53	28.16		26.11	27.14
		46.59		30.72	26.62	21.50	31.74	30.72	29.70	35.84	54.78	40.45		27.65	26.11	29.70		27.65	30.21
				33.79	29.70	26.11	34.82	32.26	38.91	38.91		45.57		31.74	29.18	33.79		31.23	34.82
				36.35	32.26	32.77	39.42	36.35	47.62	51.20		53.76		43.52	32.26	39.94		33.79	38.91
				37.89	34.82	38.40		36.86	55.81			56.32		52.74	36.35	48.64		35.84	40.45
				39.94	36.35	41.47		43.52							56.32	51.71		39.42	46.08
				43.52	40.45	47.10		48.13										42.50	50.18
				47.10		55.81		50.18										45.57	
				49.66														48.64	

* P1, P2, P3……. Pn = Identification of each sample.

Table 3
Mean values of natural frequencies obtained from the numerical simulations for each coffee plant sample.

Natural Frequencies (Hz)																		
P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16	P17	P18	P20
9.99	8.82	7.55	9.99	6.18	7.69	4.14	8.18	7.72	8.65	8.85	8.60	8.19	9.28	7.24	8.12	8.07	8.65	8.31
15.22	16.67	11.63	11.68	9.71	9.71	4.53	10.08	9.73	9.62	9.87	16.32	13.47	15.11	8.62	9.97	9.42	13.65	9.56
19.68	19.49	13.65	13.78	11.74	11.10	5.60	12.29	14.03	11.90	12.89	18.13	14.92	16.09	11.10	11.35	12.29	15.03	11.25
25.80	27.81	14.83	11.08	13.38	13.35	7.09	15.57	15.10	13.88	15.69	25.60	17.50	19.58	14.40	13.43	12.96	17.94	13.30
45.93	29.22	18.43	28.49	16.79	14.24	9.06	17.26	16.71	14.94	16.34	27.92	18.83	25.28	16.81	15.98	13.10	18.67	14.93
51.78	51.33	26.78	37.73	18.42	15.76	12.25	21.49	18.48	16.54	21.43	32.61	21.11	38.29	18.09	17.55	14.81	23.99	17.82
		30.78	40.91	21.48	18.43	14.39	23.11	20.30	18.71	27.15	38.59	24.63	58.34	20.97	19.07	16.29	32.93	18.69
		32.30	49.31	23.47	23.47	18.70	25.31	22.43	22.22	30.68	47.59	27.18		22.74	20.67	24.14	38.95	24.53
		44.04	52.49	26.12	24.43	20.38	31.30	26.65	26.43	32.34	52.48	32.31		23.05	22.87	29.09		27.40
		47.27		31.28	26.47	21.81	31.79	30.81	29.68	36.43	54.95	40.62		27.69	26.53	29.80		30.23
				36.85	29.52	25.42	35.61	32.05	39.78	41.42		45.44		31.50	31.18	31.07		35.65
				37.10	31.43	33.05	40.11	35.68	47.71	51.50		54.25		45.17	32.25	39.96		41.34
				37.95	36.83	38.96		39.92	56.47			56.40		51.58	37.49	48.84		46.01
				39.81	37.07	41.35		44.73							59.35	51.65		50.03
				44.23	40.43	48.11		48.53										
				48.10		55.05		49.86										
				49.54														

* P1, P2, P3……. Pn = Identification of each sample.

Additionally, for the Colombia cultivar, Ciro (2001) found values between 24.17 Hz and 25 Hz at the fundamental frequency for the fruit-stem system. For the second vibration mode, the resonant frequencies exceeded a value of 466 Hz. According to Ciro (2001), high frequencies are desirable for selective coffee harvesting; however, their use may be limited by practical issues. These frequencies in turn are highly de-pendent on the physical conditions and mechanical properties of the system.

The knowledge of the natural frequencies of coffee plants is essen-tial to understand the behavior of the plant when it interacts with the machine that will harvest the fruits. These frequencies can be used to design and adjust the mechanisms used for coffee harvesting.

The mean values of natural frequencies extracted in the simulations (Table 3) and used for the validation of the model were determined from the identification of frequency groups with very close values for each coffee plant sample. Each frequency value (eigenvalue) of these groups is associated with a distinct vibration mode (eigenvector). The presence of groups of vibration modes in different directions for the same frequency is an expected behavior for a system under free vibration.

The observed values for the natural frequencies in the laboratory were compared with the mean values extracted from the numerical simulation results to validate the model. For sample 19, the model did not converge with the input data; thus, it was not possible to compare the results with the experimentally obtained values, and this sample was considered as an outlier in terms of validation. The values were compared using a linear regression and the Spearman correlation test (Table 4).

In addition to predicting unknown values from known variables, linear regressions are also used to explain the values of one variable

Table 4
Adjusted R^2 values, regression equation and result of the Spearman correlation between the simulated values and the experimental values for each sample tested in the laboratory.

	Adjusted R^2	Regression Equation	ρ	p_value
Sample 1	0.9991	Y = 0.39 + 1.00X	1.00	0.002778
Sample 2	0.9978	Y = −0.43 + 1.02X	1.00	0.002778
Sample 3	0.9964	Y = −0.37 + 1.01X	1.00	0.000001
Sample 4	0.9536	Y = −1.44 + 1.00X	0.95	0.000353
Sample 5	0.9970	Y = −0.18 + 1.02X	1.00	0.000001
Sample 6	0.9958	Y = −0.08 + 1.01X	1.00	0.000001
Sample 7	0.9990	Y = 0.19 + 0.99X	1.00	0.000007
Sample 8	0.9951	Y = −0.24 + 1.03X	1.00	0.000001
Sample 9	0.9960	Y = −0.05 + 1.01X	1.00	0.000007
Sample 10	0.9990	Y = −0.27 + 1.01X	1.00	0.000001
Sample 11	0.9959	Y = −0.07 + 1.01X	1.00	0.000001
Sample 12	0.9998	Y = −0.18 + 1.00X	1.00	0.000001
Sample 13	0.9994	Y = −0.18 + 1.00X	1.00	0.000001
Sample 14	0.9991	Y = 0.04 + 0.99X	1.00	0.000397
Sample 15	0.9970	Y = −0.01 + 1.00X	1.00	0.000001
Sample 16	0.9980	Y = −1.23 + 1.07X	1.00	0.000001
Sample 17	0.9965	Y = 0.54 + 0.99X	1.00	0.000001
Sample 18	0.9986	Y = 0.16 + 0.99X	1.00	0.000049
Sample 20	0.9992	Y = −0.01 + 1.00X	1.00	0.000001

*ρ = results of the Spearman correlation.

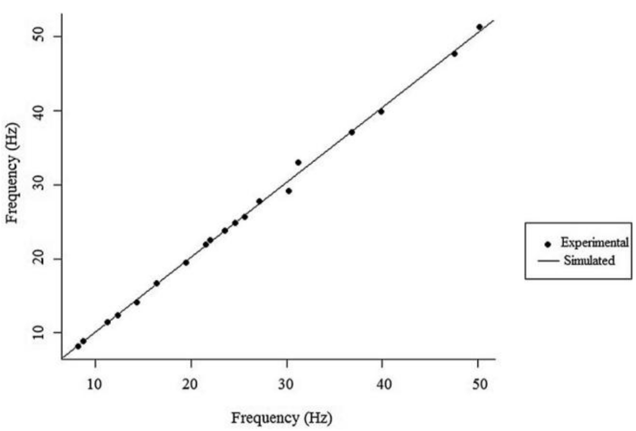

Fig. 6. Representation of the linear model that describes the association between the simulated and experimental values.

based on the values of another variable (Stevenson, 1981).

One of the main results of a regression is the coefficient of determination (adjusted R^2), as this value, which can range from −1 to 1, indicates the probability that the value of the simulated variable will be explained by the linear model (Stevenson, 1981). In this case, because all values were close to 1, linear regression is considered valid to assess the association between the simulated and experimental data.

The regression equations found for each sample (Table 2) describe the relationship between the simulated and experimental variables. The slope parameter shows how much a response variable varies as a function of the predictor variable, where a slope equal to zero re-presents a total lack of association between the variables (Stevenson, 1981). Thus, for all simulations, there was an association between the studied variables (simulated and experimental), demonstrating that the model was able to predict the behavior observed in the laboratory tests.

Except for sample 4, the ρ values for the Spearman correlation were equal to 1, which indicates that the experimental and simulated values are perfectly monotonic functions of each other. This result implies that any two pairs of data between the analyzed variables will have the same sign. Therefore, the trend observed in the analyzed data is that the simulated values follow the growth of the experimental values, as shown in Fig. 6 (Corder and Foreman, 2011).

After validation, this model can be used for numerical analysis to obtain data on the behavior of coffee plants without the need to subject them to destructive testing while also assisting in decision making in a timely manner.

Carvalho et al. (2016) observed that along the coffee plant, there are branches with different sizes, which have different mechanical stiffness patterns. The mass and stiffness of the system directly interfere with the vibration mode of the system as a whole (Rao, 2008). When a system such as this is subjected to a free vibration, the trunk experiences a certain vibration mode, and the different configurations of branches in the plant also experience different vibration modes.

As the system was subjected to a free vibration condition, it was not possible to visually identify the vibration mode in which resonance occurs in the coffee plant samples. This behavior is common in models of biological systems in which the complexity of the vibration of branches relative to the trunk makes it difficult to identify the desired vibration modes (Fig. 7).

This same difficulty was reported by Castro-García et al. (2008), who studied the dynamic behavior of olive trees. According to the authors, the independent movement of the branches relative to the trunk prevents the resonance phenomena in the main structure of the plant from being observed.

Although the visual analysis of the free vibration tests of a plant does not allow for the identification of a specific vibration mode in which fruit detachment occurs, Tinoco et al. (2014), Santos et al. (2015) and Coelho et al. (2016) indicated that the vibration modes that promote fruit detachment are the torsional, pendular and counterphase modes.

Another way to analyze this system and understand how its mechanical properties affect the simulation result is to use so-called stochastic simulations, where the input data are selected by random values in the middle of the average used. Coelho et al. (2016) used this method to study the interference of the values of the elasticity modulus and the specific mass in the result of the simulations performed to study the trunk-branch-coffee system. This technique can even be used in other areas of engineering. Kamiński and Świta (2014) worked with the stochastic finite element method to vary the input data (Young's modulus and thickness) to evaluate the resistance of steel cylindrical tubes.

4. Conclusion

In this paper, a previously developed model was used to evaluate the dynamic behavior of coffee plants through numerical simulations using the finite element technique. The previously determined input data used in the simulations took into account the anisotropy of the specimens from the trunks and branches of coffee plant samples. The results of the simulations were compared to the frequencies observed in laboratory with whole coffee plants in free vibration tests.

The method used allows the natural frequencies related to different vibration modes to be determined; however, visual analysis does not allow for the identification of the mode in which the peaks of frequency amplitudes occur and cannot determine the vibration mode that occurred at each natural frequency.

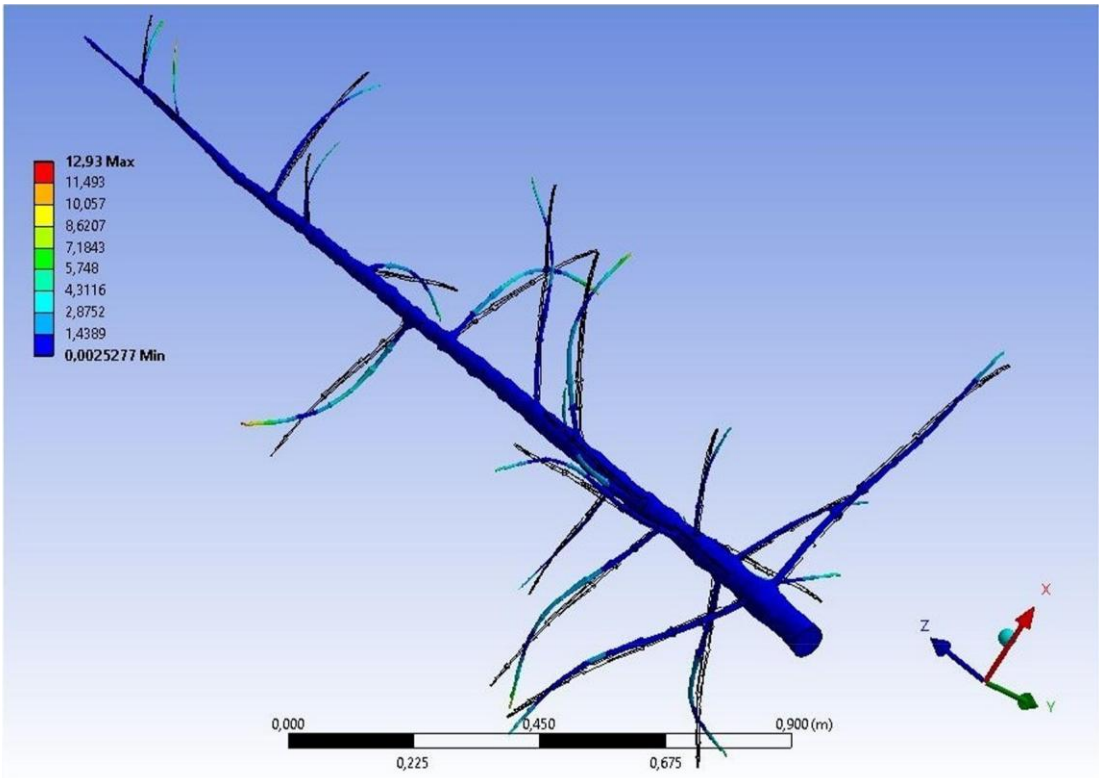

Fig. 7. Vibration mode observed in numerical simulations.

A linear correlation was found between the values of natural frequencies from laboratory tests and the values extracted from numerical simulations, validating the use of the model to predict the behavior of the coffee tree when subjected to mechanical vibrations.

The frequencies found in the laboratory tests are concentrated between 10 Hz and 30 Hz. The natural frequencies values can serve as the basis for the design and adjustment of machines that promote the detachment and harvest of coffee fruits.

Credit authorship contribution statement

Nara Silveira Velloso: Main responsible for the execution of the research project and data manipulation, besides writing and revision of the manuscript.
Ricardo Rodrigues Magalhães: Advisor, creator of the research, contributed to data analysis and writing and revision of the manuscript.
Fábio Lúcio Santos: Co-advisor and project co-supervisor; contributed to data analysis and to the writing and revision of the manuscript.
Alexandre Assis Rezende Santos: Contributed to data manipulation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors thank the Fundação de Amparo à Pesquisa do Estado de Minas Gerais (Fapemig), Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) and Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (Capes), for financial support.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.compag.2020.105552.

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