DYNAMIC BEHAVIOR OF THE COFFEE FRUIT-STEM-BRANCH SYSTEM USING STOCHASTIC FINITE ELEMENT METHOD

Andre Luiz de Freitas Coelho[1], Fábio Lúcio Santos[2], Daniel Marçal de Queiroz[3], Francisco de Assis de Carvalho Pinto[4]

(Recebido: 21 de março de 2015; aceito: 10 de agosto de 2015)

ABSTRACT: The development of an efficient machine for harvesting coffee requires comprehensive knowledge of the dynamic behavior of the plant and its parts. The finite element method is a numerical approach used to determine natural frequencies and mode shapes. However, the stochastic finite element method has not been employed for the analysis of the dynamic behavior of coffee. The aim is to determine the natural frequencies and mode shapes for the coffee fruit-stem-branch system. The natural frequencies and the mode shapes were determined by employing the stochastic finite element method, in which the elastic modulus and the specific mass were treated as random variables, and the variation in the natural frequency was obtained as a function of the variability of these properties. The natural frequencies were reduced according to the evolution of the ripening process of the fruit and stem or due to the increase in the total weight of the system due to an increase in the number of fruits attached to the stem. The natural frequencies increased with an increase in the elastic modulus or with a reduction in the specific mass.

Index Terms: Coffee, mode shapes, natural frequencies.

COMPORTAMENTO DINÂMICO DO SISTEMA FRUTO-PEDÚNCULO-RAMO DO CAFEEIRO, USANDO MÉTODO DE ELEMENTOS FINITOS ESTOCÁSTICO

RESUMO: *O desenvolvimento de máquinas eficientes para a colheita do cafeeiro exige conhecimentos sólidos sobre o comportamento dinâmico da planta. O método de elementos finitos é uma ferramenta numérica utilizada para determinar frequências naturais e modos de vibração. Porém não se tem empregado o método de elementos finitos estocástico para análise do comportamento dinâmico do cafeeiro. Assim, objetivou-se neste trabalho determinar as frequências naturais e modos de vibração do sistema fruto-pedúnculo-ramo do cafeeiro. Foram determinadas as frequências naturais e os modos de vibração empregando-se o método de elementos finitos estocástico, em que o módulo de elasticidade e a massa específica dos frutos, pedúnculo e ramos foram tratados como variáveis aleatórias, obtendo-se a variação das frequências naturais em função da variabilidade destas propriedades. As frequências naturais reduziram na medida em que se evolui o estádio de maturação dos frutos e pedúnculos ou se aumenta a massa total do sistema, dado pelo aumento do número de frutos solidários ao pedúnculo. As frequências naturais aumentaram na medida em que se elevou o módulo de elasticidade ou se reduziu a massa específica dos frutos, pedúnculos e ramos.*

Termos para indexação: *Café, frequências naturais, modos de vibração.*

1 INTRODUCTION

Coffee is an important product for the national economy. Brazil ranks as the largest producer worldwide, with an estimated production for the harvest of 2015 at 44.28 million 60-kg bags. The state of Minas Gerais is the largest producer, notable for *Coffea arabica* L. cultivation. Secondly there is the state of Espirito Santo, predominantly in growing *Coffea canephora* Pierre ex A. Froehner (COMPANHIA NACIONAL DE ABASTECIMENTO - CONAB, 2015).

In the coffee production cycle, harvesting is the most costly activity because it requires a large amount of manpower. Thus, mechanization of the harvest is a possible means to reduce costs through increases in operational capacity (BARBOSA; SALVADOR; SILVA, 2005; CIRO, 2001; OLIVEIRA et al., 2007a). Mechanical coffee harvesting is based on mechanical vibrations; inertial forces are applied to the fruit and overcome the stem attachment forces which results in fruit detachment (ARISTIZÁBAL; OLIVEROS; ALVARES, 2003; OLIVEIRA et al., 2007b; SOUZA; QUEIROZ; RAFULL, 2006).

To develop efficient harvesters, it is necessary to understand the dynamic behavior of the plant, or its parts, to be harvested (CIRO, 2001). To harvest using mechanical vibrations, the natural frequencies and mode shapes must be determined to design the machine. Studies related to the determination of the natural frequencies and mode shapes of coffee have been conducted through analytical equations, controlled laboratory

1Faculdade de Viçosa/FDV - Rua Gomes Barbosa,870 - 36.570-000 - Viçosa - MG -andrecoelho.mec@gmail.com
[2,3,4]Universidade Federal de Viçosa/UFV - Departamento de Engenharia Agrícola/DEA - Av. PH Rolfs - Campus Universitário 36.570-000 - Viçosa - MG - fabio.ls@ufv.br, queiroz@ufv.br, facpinto@ufv.br

experiments, field experiments and computational tools (ARISTIZÁBAL; OLIVEROS; ALVARES, 2003; CIRO, 2001; SANTOS et al., 2010a, 2010b, 2015). Among the computational tools, the finite element method stands out as it is based on the generation and solution of differential equations that govern the physical phenomena under study. Under this method, the analysis of the geometrical, physical and mechanical properties of the system is required (RODRÍGUEZ et al., 2006).

The finite element method has two variants: the deterministic and the stochastic. In the deterministic finite element method, input parameters with single and constant values are used so that a single output parameter value is obtained. In the stochastic finite element method, the input parameters are defined as a set of random values, so a set of results is obtained for the output parameter (BERTHAUME et al., 2012; REH et al., 2006). Random values are usually generated from models that describe the probability distribution of the parameters under analysis (STEFANOU, 2009).

The finite element method has been used to model several systems, both mechanical and biological. The studies that have been undertaken using deterministic or stochastic models include the coffee dynamic behavior (SANTOS et al., 2015), the stresses and strains in monkey skulls (BERTHAUME et al., 2012), the modal analysis of pears (JANCSÓK et al., 2001), the thermomechanical analysis of gas turbine blades, the modal analysis of automobile structures (REH et al., 2006), and the stresses and strains on teeth (PENEDO et al., 2010). However, there has been little research on applying the stochastic finite element method to the analysis of the dynamic behavior of plants, specifically coffee or its parts.

The use of the stochastic finite element method in dynamic behavior analysis is an advance in coffee research given the large variability in the geometrical, physical, and mechanical properties of coffee plants (ARISTIZÁBAL; OLIVEROS; ALVARES, 2003; RODRIGUEZ et al., 2006). Therefore, this paper is aimed at determining the natural frequencies and mode shapes of the fruit-stem, branch and fruit-stem-branch system using the stochastic finite element method. Additionally, we evaluated the influence of the ripeness stage and number of fruits attached to the same stem on the natural frequencies and mode shapes.

2 MATERIALS AND METHODS

The coffee fruit-stem, branch and fruit-stem-branch systems were modeled to determine their natural frequencies and corresponding mode shapes using the stochastic finite element method. Specifically, for the fruit-stem and fruit-stem-branch systems, situations with one, two or three fruits attached to the stem were analyzed for the green and ripe stages.

The geometrical, physical and mechanical properties studied in this work were determined experimentally by Coelho et al. (2015) using samples of the Red Catuai cultivar of *C. arabica* (Tables 1, 2 and 3) between May and July, 2013. The geometries of the models were generated by 3D-CAD software (Figures 1, 2 and 3). For the branch system (Table 3), the Poisson's ratio value was determined from the average of the results obtained by Ballarin and Nogueira (2003) and Mascia and Lahr (2006).

The mesh geometry, the setting of the physical and mechanical properties and boundary conditions, and the visualization of the solution and the results were performed with the aid of the ANSYS Mechanical APDL software, version 14.5. For mesh generation, tetrahedral elements with ten nodes were used.

The elastic modulus and the specific mass of the fruit, stem and branch were set as random variables. The dimensions and Poisson's ratio were set as constant values. Fifty values were generated for each random parameter and each component of the fruit-stem-branch system. These values were generated from the mean values and standard deviations for each parameter (Tables 1, 2 and 3) by applying the Equation (1). A random number generator program was developed in Fortran 90 language and compiled by the G95 compiler.

$$V_i = V_0 + s(2N_i - 1) \tag{1}$$

where

V_i = i-th random value;

V_0 = mean value of the parameter;

s = standard deviation of the parameter;

N_i = i-th random number with values between 0 and 1, which is generated from the algorithm proposed by Press et al. (1992).

The systems were modeled with multiple degrees of freedom and subjected to undamped free vibration, and the differential equation in matrix form (Rao, 1995). For simplification, the materials that compose the fruits, stems and branches were treated as homogeneous and isotropic.

The algorithm selected in ANSYS Mechanical APDL was the Block Lanczos algorithm that is used to solve problems with eigenvectors and eigenvalues, which provide the natural frequencies and mode shapes for systems, respectively.

TABLE 1 - The geometrical, physical and mechanical properties of the fruit in the green and ripe stages.

Ripeness Stage	Length (mm)	Diameter (mm)	Specific Mass ($g.cm^{-3}$)		Elastic Modulus (MPa)		Poisson Ratio
			Mean	Standard Deviation	Mean	Standard Deviation	
Green	16.14	12.77	1.13	0.07	15.82	5.74	0.24
Ripe	17.12	14.76	1.02	0.10	2.93	0.46	0.27

Source: physical properties obtained by Coelho et al. (2015).

TABLE 2 - The geometrical, physical and mechanical properties of the stem in the green and ripe stages.

Ripeness Stage	Length (mm)	Diameter (mm)	Specific Mass ($g.cm^{-3}$)		Elastic Modulus (MPa)		Poisson Ratio
			Mean	Standard Deviation	Mean	Standard Deviation	
Green	6.64	2.12	1.09	0.47	15.74	4.68	0.35
Ripe	6.36	2.32	1.46	0.46	23.90	8.65	0.35

Source: physical properties obtained by Coelho et al. (2015).

TABLE 3 - The geometrical, physical and mechanical properties of the branches.

Diameter (mm)	Specific Mass ($g.cm^{-3}$)		Elastic Modulus (MPa)		Poisson Ratio
	Mean	Standard Deviation	Mean	Standard Deviation	
5.06	0.90	0.11	4.65	0.94	0.34

Source: physical properties o obtained by Ballarin and Nogueira (2003), Coelho et al. (2015) and Mascia and Lahr (2006).

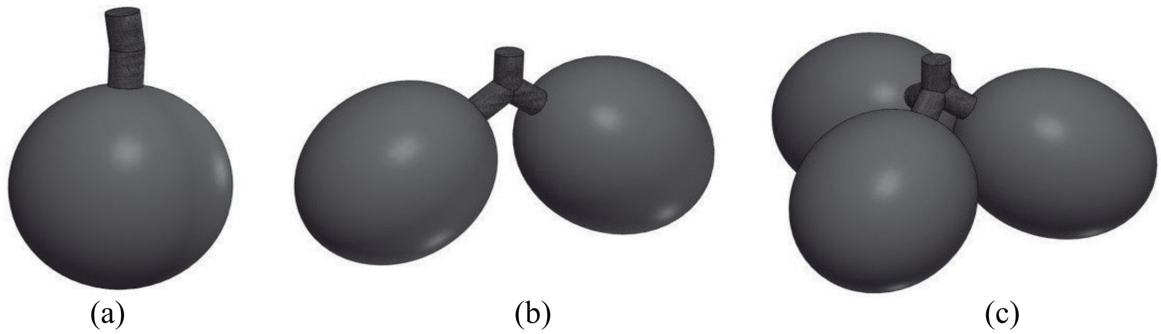

FIGURE 1 - Geometry of the fruit-stem system with (a) one, (b) two and (c) three fruits attached to the stem.

FIGURE 2 - Geometry of the branch.

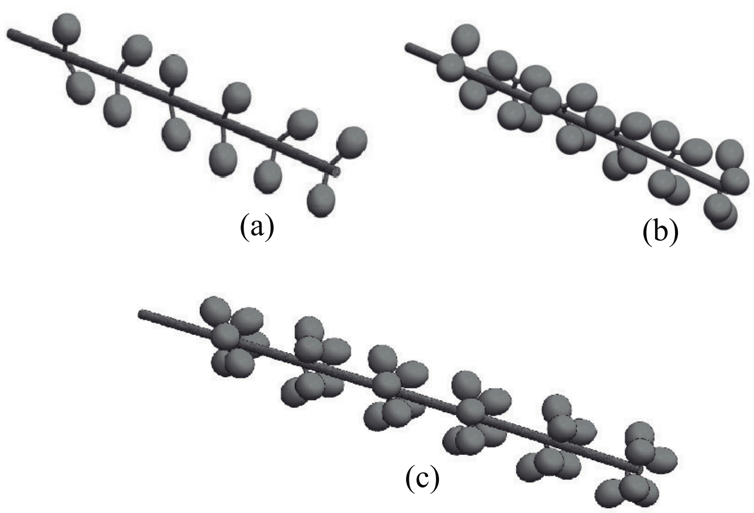

FIGURE 3 - Geometry of the fruit-stem-branch system with (a) one, (b) two and (c) three fruits grouped on each stem.

The Monte Carlo simulation method was employed to solve the stochastic model by extracting the five natural frequencies and the corresponding mode shapes. From the results, the average natural frequency was determined, and the deviation is shown as an error bar. The influence of the variation in the natural frequencies from the random variables was evaluated graphically for the green and ripe stages. The mode shapes were evaluated from its modal deflection.

3 RESULTS AND DISCUSSION

Modeling the fruit-stem system with one fruit on the stem

The range of values (Figure 4) represents the mean value and deviation of the natural frequencies due to the variability in the specific mass and the elastic modulus considered in the stochastic modeling. The natural frequencies of the fruit-stem system with a fruit attached to the stem were reduced according to the progression of the ripeness process. This behavior was also observed by Ciro (2001) and Santos et al. (2015) and is caused by a reduction in the stiffness of the stem, which is related to cell wall degradation (CASTRO; MARRACCINI, 2006).

For a selective harvest performed exclusively by mechanical vibration, the use of natural frequencies corresponding with up to the fifth mode is inefficient because there is an overlap between the frequency ranges of the green and ripe stages. Ciro (2001) determined the natural frequencies of the fruit-stem system and obtained values of 26.97 and 25.10 Hz for the shape of the first mode and 518.79 and 470.95 Hz for the shape of the second mode for the green and ripe stages, respectively. In turn, using the finite element method, Santos et al. (2015) calculated 23.2, 23.30 and 57.7 Hz and 19.9, 19.9 and 50.4 Hz, for the first, second and third natural frequencies of the green and ripe stages, respectively.

The uncertainty in the results is related to variations in the geometrical, physical and mechanical properties of the system. Moreover, these properties are associated with the characteristics of the soil, climate and the plant, such as age and variety, as well as plant management (ARISTIZÁBAL; OLIVEROS; ALVARES, 2003; RODRIGUEZ et al., 2006).

The mode shapes were similar for both ripeness stages and for different values of the elastic modulus and specific mass as there were no variations in the geometrical aspects and distribution of mass. The first and second mode shapes were characterized as pendulum displacements of the fruit-stem system in perpendicular planes, which explains the approximation of the natural frequencies of these modes. These mode shapes were also obtained by Filgueiras (2001) and Santos et al. (2015). In the third mode, the system presented a torsional displacement. The fourth and fifth mode shapes were characterized by a counter-phase pendulum displacement, in which the fruit moves in one direction and the stem in an opposite direction which was also observed by Santos et al. (2015). The detachment using the natural frequencies corresponding to the third, fourth and fifth modes should be more efficient because higher stresses may be generated in stems (ESPINOSA; RODRÍGUEZ; GUERRA, 2007) with the counter-phase pendulum and torsional displacements.

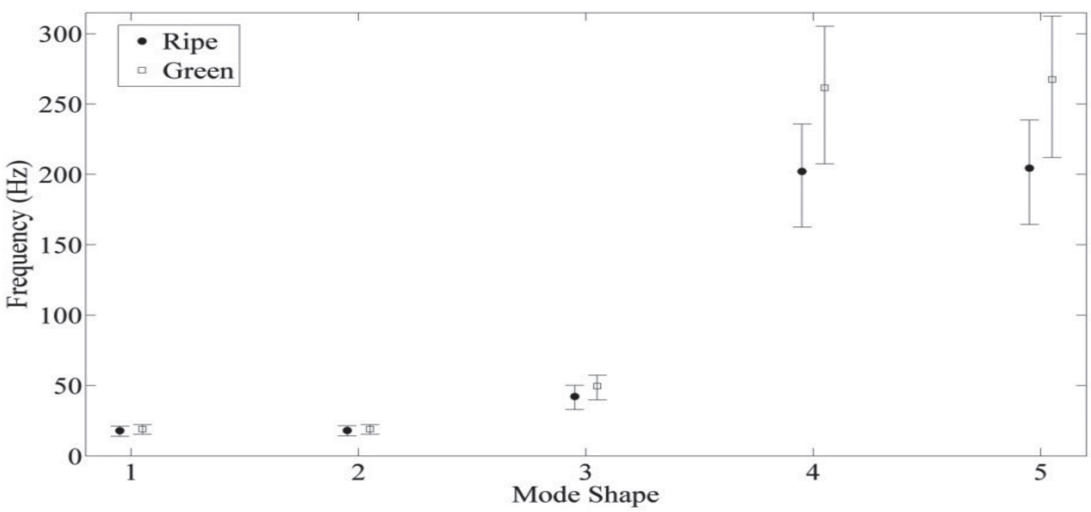

FIGURE 4 - Natural frequencies for the fruit-stem system with one fruit attached to the stem at the green and ripe stages.

Modeling of the fruit-stem system with two and three fruits on the stem

For fruit-stem systems with two and three fruits attached to the stem, the natural frequency values were reduced according to the ripening stage (Figures 5 and 6). This behavior is also related to changes in the mechanical properties of the fruits and stems due to the ripening process (CASTRO; MARRACCINI, 2006). For a selective harvest by mechanical vibration, the use of natural frequencies up to the fifth mode shape is not effective given the overlap of frequency ranges between the green and ripe stages.

For the fruit-stem system with two fruits, the first and third mode shapes were characterized as pendulum displacements in perpendicular planes. In the second mode shape, there is a rotation of the system in relation to stem attachment. In the fourth, only the fruit moves in a pendulum displacement. The fifth mode is characterized by a rotation of only the fruit. For the fruit-stem system with three fruits attached to the stem in the first mode, the system rotates. The second and third modes are characterized by pendulum displacements in perpendicular planes, and the fourth and fifth modes are represented by a pendulum displacement of the fruit. For the rotation and pendulum displacement mode shapes, the natural frequency of the fruit-stem system is reduced with increasing numbers of fruit and, consequently, the mass of the system.

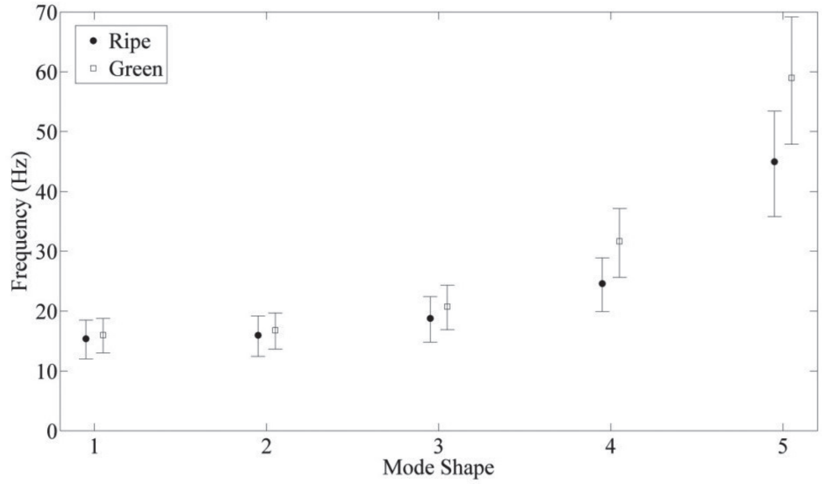

FIGURE 5 - Natural frequencies for the fruit-stem system at green and ripe stages with two fruits attached to the stem.

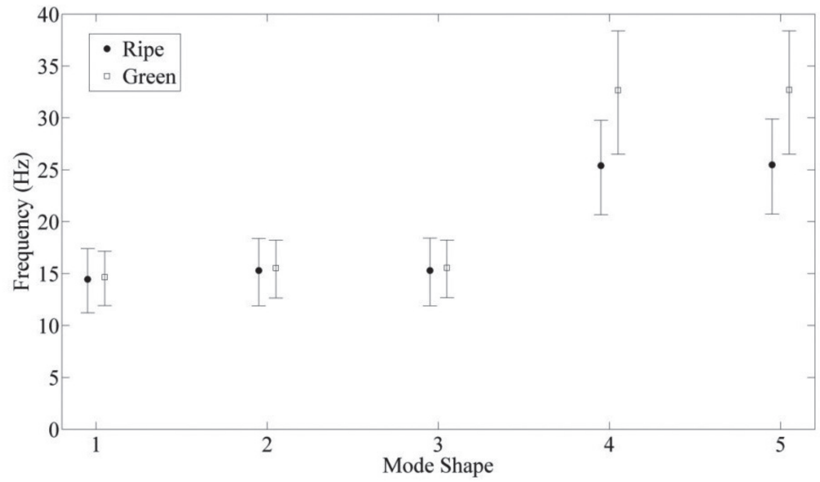

FIGURE 6 - Natural frequencies for the fruit-stem system at green and ripe stages with three fruits attached to the stem.

Modeling the coffee branch

As presented in Figure 7, the natural frequency values of the branch were higher than those found by Filgueiras (2001). In addition to the difference in the magnitude of the elastic modulus used, the differences in the results may be related to aspects of model, such as its geometry and elements used in the meshing.

In the first and second mode shapes, the branch shows a pendulum displacement in perpendicular planes. The third and fourth modes were also characterized by pendulum displacements in perpendicular planes but with counter-phase shifts. In the fifth mode shape, there was counter-phase pendulum displacement but with an increased amount of counter-phase sections. The obtained mode shapes agree with those obtained by Filgueiras (2001).

Modeling of the coffee fruit-stem-branch system

Similar to fruit-stem systems, the natural frequency of fruit-stem-branch systems reduced as the stages of ripeness advanced (Figure 8).

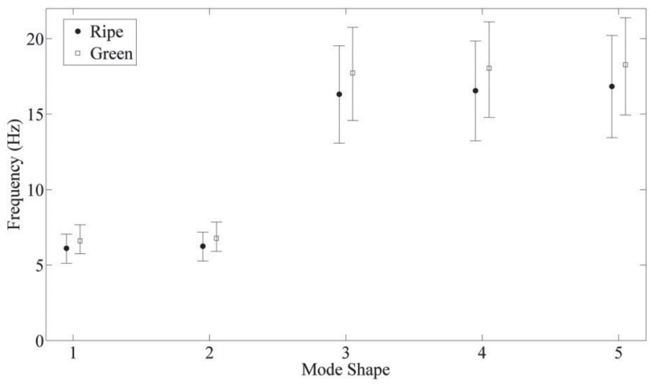

FIGURE 7 - Natural frequencies for the branch as obtained in this work and by Filgueiras (2001).

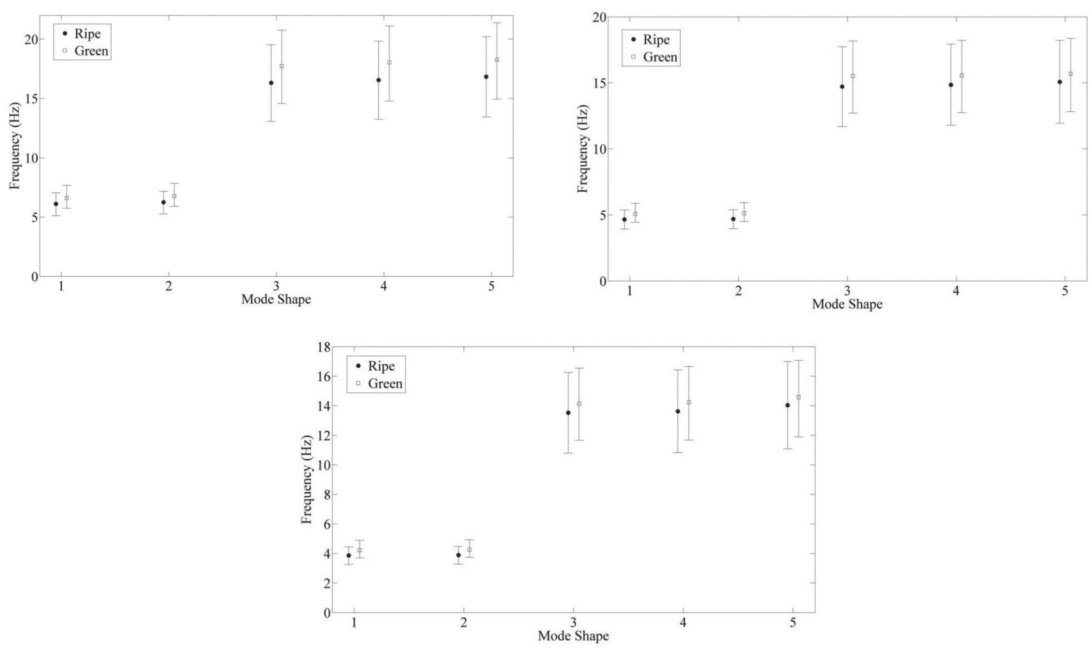

FIGURE 8 - Natural frequencies for the fruit-stem-branch system with (a) one, (b) two and (c) three fruits at the green and ripe stages.

In the three situations evaluated, one, two or three fruits attached to the stem, the first and second mode shapes were characterized by pendulum displacements in perpendicular planes of the fruit-stem-branch system. In the third, fourth and fifth modes, there were pendulum and rotational displacements.

Filgueiras (2001) modeled the coffee fruit-stem-branch system and also observed a pendulum displacement for the first and second mode shapes. In the third mode, however, a pendulum displacement in counter-phase with a branch deformation occurred. This difference can be explained by the modeling method used by the author, in which fruit masses were not displaced from the branch axis and were ignored in the fruit and stem geometries.

Thus, as occurred for the fruit-stem system, the natural frequency values in the same mode shape decreased with an increasing number of fruit attached to the same stem, i.e., the mass of the system. This was also verified by comparing the results from the fruit-stem-branch system with those of the branch, which also decreased due to the increase in mass and in agreement with Filgueiras (2001).

The results indicate that the application of frequencies of the third, fourth or fifth mode shapes will achieve the most efficient harvest. For these frequencies, the displacements mainly occurred due to stem displacement, which increases the probability of detachment. However, for a selective harvest, frequencies up to the fifth mode shape are not appropriate given the overlap of frequencies related to the green and ripe stages.

There was an increase in natural frequencies as the specific mass was reduced or the elastic modulus of the fruit, stem and branch increased (Figure 9). The increase in the natural frequency is related to a reduction in mass or an increase in the stiffness of the system.

The specific mass of the fruit varied from 918-1116 kg m-3 (22 %), and the elastic modulus of the stems varied from 15.4 to 32.5 MPa (111 %), both in relation to the experimental mean. This resulted in a range of values between 14.0 and 21.3 Hz for the first natural frequency, which represents a percentage variation of 52 %.

Therefore, the variations in the physical and mechanical properties of the fruit-stem-branch system of coffee plants significantly influenced the values of the natural frequencies. This influence stresses the importance of using the stochastic finite element method to study the dynamic behavior of coffee with the goal of developing more efficient harvesting machinery that allows for greater selectivity.

4 CONCLUSIONS

It can be concluded that:

The natural frequencies of the fruit-stem and fruit-stem-branch systems show a downward trend in response to the evolution of the ripeness process.

The natural frequencies of the systems reduce with increasing numbers of fruit due to the increase of the total mass of the systems.

In the fourth and fifth mode shapes, there are larger displacements of stems in the fruit-stem and fruit-stem-branch systems.

There is an overlap of natural frequencies relative to the green and ripe stages due to the variation in the physical and mechanical properties of the system, which may make selective harvesting by mechanical vibration impossible.

The natural frequencies of the fruit-stem, branch and fruit-stem-branch systems presented in this study increase with an increase in the elastic modulus or with the reduction in the specific mass of the fruit, stem and branch.

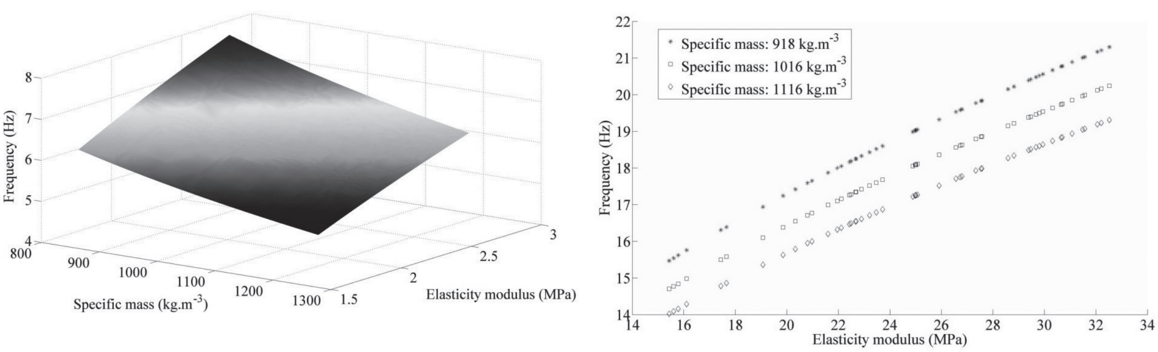

FIGURE 9 - Variation of the first natural frequency of the fruit-stem system with a ripe fruit with the variability of the specific mass of the fruit and the elastic modulus of the stem for (a) a response surface and (b) cuts.

5 ACKNOWLEDGMENTS

The National Council for Scientific and Technological Development (CNPq) and the Foundation for Research Support of the State of Minas Gerais (FAPEMIG) are acknowledged for the financial support of the project's development.

6 REFERENCES

ARISTZÁBAL, I. D.; OLIVEROS, T. C. E.; ALVARES, M. F. Mechanical harvest of coffee applying circular and multidirectional vibrations. **Transactions of the ASAE**, Saint Joseph, v. 46, n. 2, p. 197-204, 2003.

BALLARIN, A. W.; NOGUEIRA, M. Caracterização elástica da madeira de eucalyptus citriodora. **Cerne**, Lavras, v. 9, n. 1, p. 66-80, 2003.

BARBOSA, J. A.; SALVADOR, N.; SILVA, F. M. Desempenho operacional de derriçadoras mecânicas portáteis, em diferentes condições de lavouras cafeeiras. **Revista Brasileira de Engenharia Agrícola e Ambiental**, Campina Grande, v. 9, n. 1, p. 129-132, 2005.

BERTHAUME, M. A. et al. Probabilistic finite element analysis of a craniofacial finite element model. **Journal of Theoretical Biology**, Michigan, v. 300, n. 1, p. 242-253, 2012.

CASTRO, R. D.; MARRACCINI, P. Citology, biochemistry and molecular changes during coffee fruit development. **Brazilian Journal of Plant Physiology**, Campos dos Goytacuzes, v. 18, p. 175-199, 2006.

CIRO, H. J. Coffee harvesting I: determination of the natural frequencies of the fruit stem system in coffee tress. **Applied Engineering in Agriculture**, Saint Joseph, v. 17, n. 4, p. 475-479, 2001.

COELHO, A. L. F. et al. Determinação das propriedades geométricas, físicas e mecânicas do sistema fruto-pedúnculo-ramo do cafeeiro. **Revista Brasileira de Engenharia Agrícola e Ambiental**, Campina Grande, v. 19, n. 3, p. 286-292, 2015.

COMPANHIA NACIONAL DE ABASTECIMENTO. **Acompanhamento da safra brasileira:** café safra 2015 segunda estimativa, junho/2015. Disponível em: <http://www.conab.gov.br/OlalaCMS/uploads/arquivos/15_06_10_09_24_57_boletim_cafe_junho_2015.pdf>. Acesso em: 21 jun. 2015.

ESPINOSA, B. G.; RODRÍGUEZ, A. M.; GUERRA, L. O. Búsqueda de modos de vibración apropiados para la cosecha selectiva del café. **Revista Ciências Técnicas Agropecuárias**, La Habana, v. 16, n. 1, p. 1-6, 2007.

FILGUEIRAS, W. H. **Modelagem da planta de café por elementos finitos para estudos de colheita por vibração**. 2001. 81 f. Dissertação (Mestrado em Engenharia Agrícola) - Universidade Federal de Viçosa, Viçosa, 2001.

JANCSÓK, P. T. et al. Investigation of the effect of shape on the acoustic response of 'conference' pears by finite element modeling. **Postharvest Biology and Technology**, Washington, v. 23, n. 1, p. 1-12, 2001.

MASCIA, N. T.; LAHR, F. A. R. Remarks on orthotropic elastic models applied to wood. **Materials Research**, São Carlos, v. 9, n. 3, p. 301-310, 2006.

OLIVEIRA, E. et al. Custos operacionais da colheita mecanizada do cafeeiro. **Pesquisa Agropecuária Brasileira**, Brasília, v. 42, n. 6, p. 827-831, jun. 2007a.

OLIVEIRA, E. et al. Influência da vibração das hastes e da velocidade de deslocamento da colhedora no processo de colheita mecanizada do café. **Revista Engenharia Agrícola**, Jaboticabal, v. 27, n. 3, p. 714-721, 2007b.

PENEDO, N. D. et al. Simulação 3D de movimento ortodôntico. **Dental Press Journal of Orthodontics**, Maringá, v. 15, n. 5, p. 98-108, 2010.

PRESS, W. H. et al. **Numerical recipies in FORTRAN:** the art of scientific computing. 2nd ed. New York: Cambridge University Press, 1992. 936 p.

RAO, S. S. **Mechanical vibrations**. 3rd ed. New York: A. Wesley, 1995. 912 p.

REH, S. et al. Probabilistic finite element analysis using ANSYS. **Structural Safety**, England, v. 28, n. 1/2, p. 17-43, 2006.

RODRÍGUEZ, A. M. et al. Determinácion de propriedades físico-mecánicas de los frutos de café (Coffea arábica variedade Catuai) relacionadas con la cosecha mecanizada. **Revista Ciências Técnicas Agropecuárias**, La Habana, v. 15, n. 3, p. 22-27, 2006.

SANTOS, F. L. et al. Analysis of the coffee harvesting process using an electromagnetic shaker. **Acta Scientiarum. Agronomy**, Maringá, v. 32, n. 3, p. 373-378, 2010a.

SANTOS, F. L. et al. Efeito da frequência e amplitude de vibração sobre a derriça de frutos de café. **Revista Brasileira de Engenharia Agrícola e Ambiental**, Campina Grande, v. 14, n. 4, p. 425-431, 2010b.

SANTOS, F. L. et al. Simulation of the dynamic behavior of the coffee fruit-stem system using finite element method. **Acta Scientarium. Technology**, Maringá, v. 37, n. 1, p. 11-17, jan./mar. 2015.

SOUZA, C. M. A.; QUEIROZ, D. M.; RAFULL, L. Z. D. Derriçadora portátil na colheita total e seletiva de frutos do cafeeiro. **Pesquisa Agropecuária Brasileira**, Brasília, v. 41, n. 11, p. 1637-1642, nov. 2006.

STEFANOU, G. The stochastic finite element method: past, present and future. **Computer Methods Applied Mechanics and Engineerings**, Texas, v. 198, n. 9/12, p. 1031-1051, 2009.