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Simulation of the dynamic behavior of the coffee fruit-stem system using finite element method

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ABSTRACT. Mechanical harvesting can be considered an important factor to reduce the costs in coffee production and to improve the quality of the final product. Coffee harvesting machinery uses mechanical vibrations to accomplish the harvesting. Therefore, the determination of the natural frequencies of the fruit-stem systems is an essential dynamic parameter for the development of mechanized harvesting system by mechanical vibrations. The objective of this study was to develop a three-dimensional finite element model to determine the natural frequencies and mode shapes of the coffee fruit-stem systems, considering different fruit ripeness. Moreover, it was carried out a theoretical study, using the finite element three-dimensional model, based on the linear theory of elasticity, for determining the generated stress in a coffee fruit-stem system, during the harvesting process by mechanical vibration. The results showed that natural frequencies decrease as the ripeness condition of the fruit increases. Counter-phase mode shape can provide better detachment efficiency considering the stress generation on coffee fruit-stem system during the harvesting by mechanical vibrations and presented a difference greater than 40 Hz between the natural frequencies of the green and ripe fruit.

Keywords: coffee harvesting, mechanization, mechanical vibrations.

Simulação do comportamento dinâmico do sistema fruto-pedúnculo do café empregando o método de elementos finitos

RESUMO. A colheita mecanizada pode ser considerada como um importante fator na redução de custos de produção e na obtenção de café de qualidade. Um dos princípios mais difundidos e empregados em máquinas colhedoras de frutos é o de vibrações mecânicas. Logo, a determinação das frequências naturais dos sistemas fruto-pedúnculo é requisito básico para o desenvolvimento de sistemas de colheita por vibrações mecânicas. O objetivo desse trabalho foi o desenvolvimento de um modelo tridimensional em elementos finitos do sistema fruto-pedúnculo, para a determinação das frequências naturais e modos de vibração para os diferentes graus de maturação do sistema fruto-pedúnculo. Adicionalmente, foi realizado um estudo teórico para a determinação dos esforços gerados em um sistema fruto-pedúnculo quando submetido a vibrações mecânicas. Os resultados mostraram que as frequências naturais diminuem à medida que o grau de maturação dos frutos aumenta. O modo de vibração em contra-fase pode proporcionar melhor eficiência de derriça por gerar níveis de tensões mais acentuados na união entre o fruto e o pedúnculo, pela sua configuração geométrica. Para o modo de vibração em contra-fase o intervalo entre as frequências naturais para os graus de maturação verde e cereja foi superior a 40 Hz.

Palavras-chave: colheita de café, mecanização, vibrações mecânicas.

Introduction

Coffee price is directly associated with quality parameters. Fruit selection during the harvesting has an important role in the quality of the final product (CIRO, 2001). Coffee harvesting can be considered the most expensive operation related to the coffee production chain due to the large labor contingent demanded. Additionally, this operation affects the final quality of the coffee (OLIVEIRA et al., 2007).

Mechanical harvesting can be considered an important factor to reduce the costs in coffee production, since cost reduction is directly related to the mechanization level employed in the execution of operations (BARBOSA et al., 2005; OLIVEIRA et al., 2007). However, this mechanization process is influenced by the variability of many factors such as the structure, size and form of the plants and the non-uniformity of fruit ripeness. Therefore, the use of mathematical modeling and the computational simulation techniques becomes an important tool to perform detailed analysis of the coffee harvesting process. Finite element method has been used in simulation of many mechanical and biological systems (HUEBNER et al., 2001; ZIENKIEWICZ et al., 2005). This method has been employed on the study of the fruit dynamic behavior the determination of the natural frequencies and mode shapes (NOURAIN et al., 2005; SONG et al., 2006). Alternatively, Lewis et al. (2007) applied the finite element method on determination of the mechanical damages in apples, through the stress analysis, during its transportation.

Coffee machinery harvesters have used mechanical vibrations to accomplish the harvesting. Machinery and equipment that use this principle are able to detach the fruit from the plants using vibrational energy through the appropriate combination of frequency and amplitude (SESSIZ; ÖZCAN, 2006; POLAT et al., 2007; PEZZI; CAPRARA, 2009; TORREGROSA et al., 2009; SANTOS et al., 2010). Several studies have been carried out in order to modeling the fruit-stem systems to understand its dynamic behavior during the harvesting process by mechanical vibrations (TSATSARELIS, 1987; CIRO, 2001; MATEEV; KOSTADINOV, 2004; WANG; LU, 2004).

Therefore, the determination of the natural frequencies of the fruit-stem systems is an essential dynamic parameter for the development of mechanized harvesting systems by mechanical vibrations. According Aristzabal et al. (2003), the fruit-stem system natural frequencies are one of the main characteristics needed for design fruit harvesting machines, since the excitation of the fruit-stem system in those frequencies allow a maximal response, which will result in the detachment of the fruit.

The objective of this study was to develop a three-dimensional finite element model to determine the natural frequencies and mode shapes of the coffee fruit-stem systems, considering different fruit ripeness. Moreover, it was carried out a theoretical study, using the finite element three-dimensional model, based on the linear theory of elasticity for determining the generated stress in a coffee fruit-stem system during the harvesting process by mechanical vibration.

Material and methods

Geometric, physical and mechanical properties of the coffee fruit-stem system

Geometric, physical and mechanical properties were determined from coffee fruit-stem samples collected randomly from the Catuaí Vermelho and Mundo Novo varieties, considering the ripeness condition of the fruit. In this work, three ripeness conditions were used: ripe (red cherries), half-ripe and green.

The geometric characterization of the fruit-stem systems was performed using digital images obtained from five megapixels resolution camera. It was obtained 50 digital images for each of the ripeness condition considered. The main dimensions of the fruit-stem systems were determined by Computer Aided Design (CAD) software, such as length and diameter of stem and fruit.

The average mass of coffee fruit was determined with a scale with an accuracy of 0.001 g, the average mass being obtained from 100 samples for each ripeness condition from each variety (Catuaí Vermelho and Mundo Novo).

The average volume of coffee fruit was obtained by water immersion of 100 fruits in a 1,000 mL graduated flask with 0.5 mL divisions. This procedure was carried out for each ripeness condition of the both varieties considered in this work. From the relation between average mass and volume of coffee fruit, it was determined the average specific mass.

Physical and geometric properties of the coffee fruit-stem systems were submitted to analysis of variance at a 5% significant level, considering a completely randomized design. The effect of the variety and ripeness condition of the coffee fruit was determined by Tukey test, using 5% of probability.

Modulus of elasticity used on the characterization of the dynamic behavior of the coffee fruit-stem system was obtained by Yung and Fridley (1974).

Finite Element Modeling

Three dimensional models from the finite element method generate a significant improvement in modeling results, which is possible by the use of a greater number of degrees of freedom on the physical system representation (HUEBNER et al., 2001; ZIENKIEWICZ et al., 2005).

From a four node tetrahedral element, a theoretical formulation can be developed to obtain the element mass matrix $[M]^{(e)}$, stiffness matrix $[K]^{(e)}$ and damping matrix $[C]^{(e)}$, considering that a displacement field of the tetrahedral element can be obtained using linear interpolation (L) among the element nodes (BATHE, 1996; HUEBNER et al., 2001; ZIENKIEWICZ et al., 2005).

The stiffness matrix $[K]^{(e)}$ for the tetrahedral element can be determined from the relationship between the nodal displacements matrix $[B]^{(e)}$, the material or module matrix $[D]^{(e)}$ of the analyzed system and the element volume, according to the equation 1. $[B]^{(e)} = [L][N]$

$$[K]^{(e)} = \left([B]^{(e)}\right)^T [D][B]^{(e)} V \quad (1)$$

Equation 2 allows the determination of the matrix $[B]^{(e)}$, which relates the matrix of differential operators and interpolation matrix.

$$[B]^{(e)} = [L][N] \quad (2)$$

where:

$$[L]^T = \begin{bmatrix} \frac{\partial}{\partial x} & 0 & 0 & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} & 0 \\ 0 & \frac{\partial}{\partial y} & 0 & \frac{\partial}{\partial x} & 0 & \frac{\partial}{\partial z} \\ 0 & 0 & \frac{\partial}{\partial z} & 0 & \frac{\partial}{\partial x} & \frac{\partial}{\partial y} \end{bmatrix}$$

$$[N] = \begin{bmatrix} L_1 & 0 & 0 & L_2 & 0 & 0 & L_3 & 0 & 0 & L_4 & 0 & 0 \\ 0 & L_1 & 0 & 0 & L_2 & 0 & 0 & L_3 & 0 & 0 & L_4 & 0 \\ 0 & 0 & L_1 & 0 & 0 & L_2 & 0 & 0 & L_3 & 0 & 0 & L_4 \end{bmatrix}$$

The material matrix, presented in equation 2, can be determined based on Hooke's law for a homogeneous and isotropic material, according to equation 3.

$$[D] = \frac{E}{(1+\mu)(1-2\mu)} \begin{bmatrix} 1-\mu & \mu & \mu & 0 & 0 & 0 \\ \mu & 1-\mu & \mu & 0 & 0 & 0 \\ \mu & \mu & 1-\mu & 0 & 0 & 0 \\ 0 & 0 & 0 & (1-2\mu)/2 & 0 & 0 \\ 0 & 0 & 0 & 0 & (1-2\mu)/2 & 0 \\ 0 & 0 & 0 & 0 & 0 & (1-2\mu)/2 \end{bmatrix} \quad (3)$$

where:

E = elasticity modulus, N m^{-2};

μ = Poisson's ratio.

Equation 4 allows the determination of the mass matrix $[M]^{(e)}$, which can be calculated by the integration over volume ($V^{(e)}$) of the three-dimensional sub-domain, composed by a tetrahedral element, using the element shape function $[N]$.

$$[M]^{(e)} = \int \rho [N]^T [N] dV \quad (4)$$

where:

ρ = specific mass of the material, kg m^{-3}.

Similarly to the mass matrix $[M]^{(e)}$, the damping matrix $[C]^{(e)}$ can be obtained from equation 5.

$$[C]^{(e)} = \int c [N]^T [N] dV \quad (5)$$

where:

c = damping coefficient, N s m^{-1}.

For isoparametric elements, the transformation of the natural coordinates to the local coordinates (ξ, η, ζ) must be performed. Thus, in the coordinate transformation procedure the expressions $\partial N_i/\partial x$, $\partial N_i/\partial y$ and $\partial N_i/\partial z$ must be written in terms of ξ, η and ζ. From the transformation of the coordinates, the element matrices can be obtained numerically using the Gauss-Legendre integration method (REDDY, 1993; BATHE, 1996; HUEBNER et al., 2001; ZIENKIEWICZ et al., 2005).

Natural Frequencies and Mode Shapes

The natural frequencies and modes of vibration of a system can be obtained from the formulation and solution of an eigenvalue and eigenvector problem. Equation 6 represents the natural vibration of a system, which is characterized as free undamped vibration.

$$[M]\{\ddot{v}\} + [K]\{v\} = \{0\} \quad (6)$$

where:

$\{\ddot{v}\}$ = acceleration vector, m s^{-2};

$\{v\}$ = displacement vector, m.

The eigenvalues and eigenvectors can be calculated assuming that the free vibrations are harmonic, such that $\{v\} = \{\varphi\}e^{i\omega_i t}$. Thus, the natural frequencies (eigenvalues) and mode shapes (eigenvectors) may be obtained solving the equation 6.

Coffee Fruit-Stem System Transient Response

In structural dynamic analysis, the governing equations are written as second order ordinary differential equations (RAO, 1995). According to Bathe (1996), equation 7 corresponds to linear dynamic response of a system submitted to a time dependent force, which can be employed in a finite element analysis.

$$[M]\{\ddot{v}\} + [C]\{\dot{v}\} + [K]\{v\} = \{F(t)\} \quad (7)$$

In a finite element method, mass matrix $[M]$, damping matrix $[C]$ and stiffness matrix $[K]$ correspond to global matrices, while displacement vector $\{v\}$, velocity vector $\{\dot{v}\}$, acceleration vector $\{\ddot{v}\}$ and force vector $\{F(t)\}$ correspond to global vectors. The global matrices and the global vectors are obtained from the assembly of the elements, using finite element procedures.

The nodal displacements are determined using numerical integration procedures from the set of equations that are governing the system dynamic behavior. According to Huebner et al. (2001), the central difference method, the Newmark method and the modal superposition method correspond to numerical procedures commonly employed in the finite element method.

The nodal displacements (*u*, *v* and *w*) are used in elastic strain vector $\{\varepsilon\}$. The elastic strain components ε_{xx}, ε_{yy} and ε_{zz} are the normal strain of a system submitted to external forces (SEGERLIND, 1984; HUEBNER et al., 2001; ZIENKIEWICZ et al., 2005). The components ε_{xy}, ε_{xz} and ε_{yz} are the shear strain.

From equation 8, the stress vector $\{\sigma\}$ can be calculated using Hooke's law for a homogeneous and isotropic material. The stress vector is composed by normal stress components and shear stress components.

$$\{\sigma\} = [D]\{\varepsilon\} \quad (8)$$

For the analysis of the generated stress in the fruit-stem system, it was used the von Mises criterion, which is obtained from the normal stress components calculated for each element. Equation 9 represents the equivalent von Mises stress σ_e composed by the normal stress components.

$$\sigma_e = \frac{1}{\sqrt{2}}\sqrt{(\sigma_{xx}-\sigma_{yy})^2 + (\sigma_{yy}-\sigma_{zz})^2 + (\sigma_{zz}-\sigma_{xx})^2} \quad (9)$$

Implementation, simulation and post-processing

The domain discretization, composed by coffee fruit-stem system, was performed using the TetGen software version 1.4.2, which allows the generation of unstructured tetrahedral meshes. It was used a standard mesh, with elements 1,988 nodes and 10,216 elements, for the determination of modal parameters and transient analysis of the fruit-stem systems. The basic dimensions of the mesh were corrected for each geometrical dimensions means of the fruit-stem system in the radial and axial directions. Natural frequencies and mode shapes of the coffee fruit-stem system were determined using a computer program specially devised for that. The solution of the eigenvalue and eigenvector problem was carried out by subspace numerical method, according to Bathe (1996). The dynamic behavior of the coffee fruit-stem system was studied by the simulation of the system submitted to forces during a specific period of time. The solution of the finite element model was obtained using Newmark Beta numerical integration method (HUEBNER et al., 2001).

All computer programs were developed in g95 compiler, which is a FORTRAN 90 programming language. All simulations were performed using the UBUNTU Linux distribution, stable version 11.04.

Results and discussion

Geometric, physical and mechanical properties

Tables 1 and 2 present the average dimensions obtained for fruit-stem systems considering the coffee ripeness conditions.

Table 1. Coffee stem average dimensions for Catuaí Vermelho and Mundo Novo varieties.

Ripeness condition	Stem length (mm)		Stem diameter (mm)	
	Catuaí Vermelho	Mundo Novo	Catuaí Vermelho	Mundo Novo
Green	6.66 Ba	6.07 Ba	2.16 Aa	2.07 Ab
Half-ripe	7.66 Aa	7.31 Aa	2.17 Aa	2.12 ABa
Ripe	7.81 Aa	7.67 Aa	2.23 Aa	2.22 Ba

Means followed by equal letters (uppercase to the ripeness condition and lowercase to the variety) do not differ by Tukey test at 5% probabilNity.

Table 2. Coffee fruit average dimensions for Catuaí Vermelho and Mundo Novo varieties.

Ripeness condition	Fruit diameter (mm)		Fruit length (mm)	
	Catuaí Vermelho	Mundo Novo	Catuaí Vermelho	Mundo Novo
Green	12.81 Aa	11.94 Ab	15.88 Aa	15.69 Aa
Half-ripe	14.22 Ba	14.27 Ba	16.90 Ba	17.11 Ba
Ripe	14.22 Ba	15.05 Cb	17.11 Ba	17.58 Bb

Means followed by equal letters (uppercase to the ripeness condition and lowercase to the variety) do not differ by Tukey test at 5% probability.

The stem length for half-ripe and ripe fruit presented the greater dimensions for both varieties in this study (Table 1). Additionally, half-ripe and ripe fruit dimensions presented no significant difference, except for diameter of the Mundo Novo variety fruit. In Table 2, it can be observed that the greater fruit dimensions occurred for ripe fruit of the Mundo Novo variety.

Table 3 shows that the largest average masses were obtained for Catuaí Vermelho variety, except for the green ripeness condition. It may be observed that the coffee fruit masses were different in each ripeness condition considered.

Table 3. Coffee fruit average mass for Catuaí Vermelho and Mundo Novo varieties.

Fruit Mass (g)			
Variety	Ripeness Condition		
	Green	Half-ripe	Ripe
Catuaí Vermelho	1.211 Aa	1.543 Ba	1.690 Ca
Mundo Novo	1.176 Aa	1.438 Bb	1.566 Cb

Means followed by equal letters (uppercase to the ripeness condition and lowercase to the variety) do not differ by Tukey test at 5% probability.

Table 4 shows the results for average specific mass of coffee fruit considering the ripeness condition. According to these results, the specific mass of the coffee tends to present a decreasing behavior in relation to the ripeness evolution. Similar behavior was observed by Corrêa et al. (2002), who concluded that the moisture loss influences the reduction of fruit dimensions, this effect reduces the fruit roundness and sphericity, which directly changes the fruit specific mass.

Table 4. Coffee fruit average specific mass for Catuaí Vermelho and Mundo Novo varieties.

Fruit Specific Mass (g cm^{-3})			
Variety	Ripeness Condition		
	Green	Half-ripe	Ripe
Catuaí Vermelho	1.199	1.110	1.090
Mundo Novo	1.197	1.072	1.072

Natural Frequencies and Mode Shapes

Results of the natural frequencies are presented in Table 5 for coffee fruit-stem system. Natural frequencies for Catuaí Vermelho and Mundo Novo varieties were obtained from the three-dimensional finite element model. According Láng (2006), modal parameters are fundamental to analysis and development of the harvesting machineries project, mainly, when these machineries work by mechanical vibrations.

Table 5. Coffee fruit-stem natural frequencies for Catuaí Vermelho and Mundo Novo varieties.

	Natural Frequencies (Hz)					
	Green		Half-ripe		Ripe	
	Catuaí Vermelho	Mundo Novo	Catuaí Vermelho	Mundo Novo	Catuaí Vermelho	Mundo Novo
1	23.2	23.2	21.8	23.6	19.9	20.6
2	23.3	23.3	21.9	23.7	19.9	20.7
3	57.7	59.9	53.6	55.6	50.4	49.6
4	295.7	300.6	275.5	292.8	254.2	257.4
5	297.3	302.2	276.8	294.2	255.3	258.6

In Table 5, natural frequencies 1, 2, 4 and 5 represent the frequencies of lateral vibrations of the system, according to the number of degrees of freedom and the boundary conditions considered in the analysis. Ciro (2001) obtained similar results for the first natural frequency from a simple two degrees of freedom model; however, the model used did not allow the evaluation of the higher frequencies.

Natural frequencies 1 and 2 present a short interval between the frequencies of green fruit and ripe fruit. This condition represents the difficulty to perform selective harvesting by mechanical vibrations. Natural frequency 3 presents an interval below 11 Hz, which could represent a better potential for coffee selective harvesting. However, natural frequencies 4 and 5 presented a difference greater than 40 Hz between green and ripe fruit, as illustrated by Figure 1.

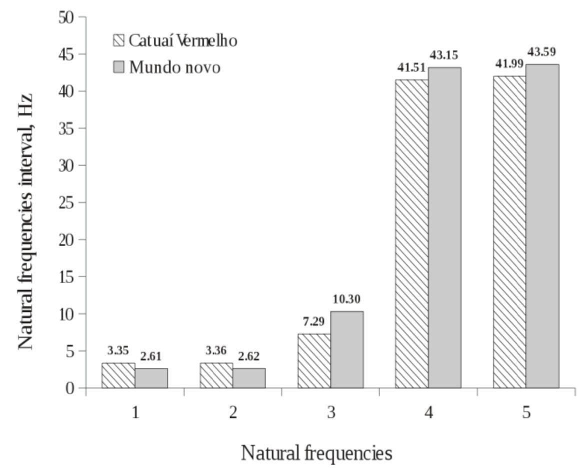

Figure 1. Interval between natural frequencies of green fruit and ripe fruit for Catuaí Vermelho and Mundo Novo varieties.

Figure 1 shows that for the highest natural frequencies, which are associated to complex mode shapes, it could be possible to perform a selective harvesting by mechanical vibrations.

Figure 2 presents the mode shapes associated with the natural frequencies of the coffee fruit-stem systems (Table 5): pendular mode shape associated with natural frequencies 1 and 2; torsional mode shape associated with natural frequencies 3 and counter-phase mode shape associated with natural frequencies 4 and 5.

Considering the stress on the region of attachment between the fruit and the stem during a harvesting process by mechanical vibration, the torsional and counter-phase mode shapes would generate a greater stress concentration in this region, improving the detachment efficiency. Additionally, the natural frequencies associate to these modes shapes have a greater potential for the selective harvesting, as shown in Figure 1.

However, the machines employed in coffee mechanical harvesting by mechanical vibration, operate at lower frequencies, which are associated to pendular mode shape, and would not allow the selective harvesting from mechanical vibrations (SANTOS et al., 2010; CIRO, 2001).

Coffee fruit-stem system transient response

Normal and shear stresses on coffee fruit-stem system were calculated from the nodal displacements of the finite element model. The normal and shear components of stress were converted into the von Mises equivalent stress.

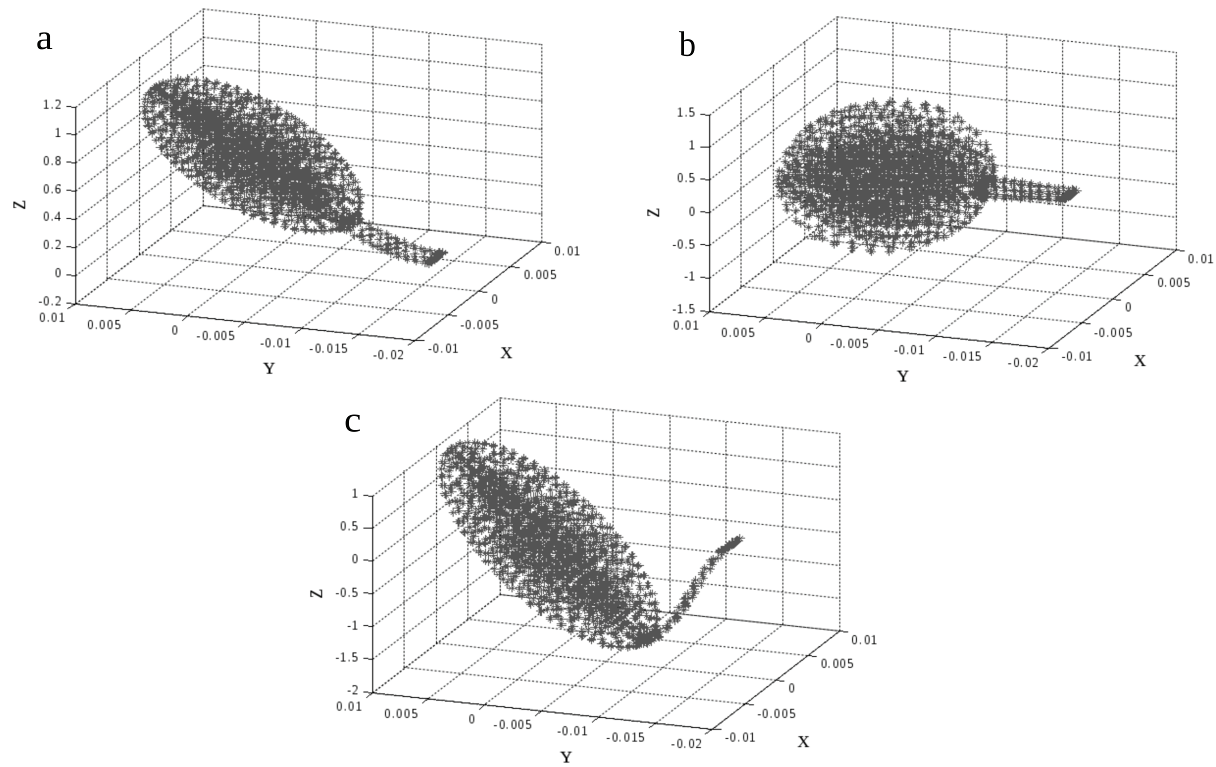

Figure 2. Dimensionless mode shapes of the coffee fruit-stem systems: (a) pendular mode shape, (b) torsional mode shape and (c) counter-phase mode shape.

In Table 6 are presented the equivalent von Mises stresses obtained on the region of attachment between the fruit and the stem for resonant frequencies.

The greater von Mises equivalent stress was obtained in region of attachment between the fruit and the stem. The ripeness condition influences the stresses generated during the harvesting process by mechanical vibrations, considering that fruit-stem systems on green ripeness condition present greater stresses during the simulation (Table 6).

Table 6. Equivalent von Mises stresses on coffee fruit-stem system for Catuaí Vermelho and Mundo Novo varieties considering green and ripe ripeness conditions.

Ripeness Condition	Natural Frequencies	Average Stress on region of attachment between the fruit and stem (MPa)	
		Catuaí Vermelho	Mundo Novo
Green	1st	7.18	7.70
	2nd	8.69	9.96
	3rd	36.06	44.11
Ripe	1st	3.39	2.14
	2nd	4.25	2.64
	3rd	13.07	7.22

Such behavior can be explained by the higher stiffness of the fruit-stem system on green ripeness compared to ripe ripeness condition. Similar behavior was observed by Silva et al. (2010) analyzing the detachment average strength of coffee fruit. The authors observed that the detachment average strength was higher for the green ripeness condition than ripe ripeness condition for both the varieties. These results indicate that is possible to perform selective harvesting using mechanical vibrations by appropriate selection of excitation frequency associated to the modal parameters of the system.

Additionally, the highest stress occurred in the region of attachment between the fruit and the stem, which can be attributed to the geometric configuration of the fruit-stem system, similar to a cantilever beam with a concentrated mass at its end.

Conclusion

The natural frequencies of the fruit-stem systems are dependent on the geometrical, physical and mechanical properties and on the ripeness condition of the fruit.

The highest stress was obtained in the region of attachment between the fruit and the stem for both varieties.

Counter-phase mode shape can provide better detachment efficiency considering the stress generation on coffee fruit-stem system during the harvesting by mechanical vibrations.

Counter-phase mode shape presented a difference greater than 40 Hz between green and ripe fruit for the Catuaí Vermelho and Mundo Novo varieties, which represents a great potential for selective harvesting by mechanical vibrations.

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