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DETERMINATION OF DETACHMENT FREQUENCIES OF RIPE COFFEE FRUITS (COFFEA ARABICA VAR. COLOMBIA) BY MEANS OF A NUMERICAL AND EXPERIMENTAL APPROACH

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Abstract: In this study, it is proposed an experimental and numerical approach to identify a bandwidth of harmonic frequencies where ripe fruits of Coffea arabica L. var. Colombia can be selectively stimulated. For this purpose, a geometric model was designed computationally to represent the topology of the coffee fruit-peduncle system in all ripening stages. Using analytical models and pseudo experimental data, the mechanical properties were estimated to carry out a finite element analysis of the system. It was verified with a detachment model that a fruit can be detached when a specific harmonic force (mechanical vibrations) is applied on the fruits in determined frequencies which correspond to the second vibration mode of the fruits. Results indicate that dynamic excitations between 130 to 150 Hz could detach only ripe fruits, since fruits that were in other ripening stages were not stimulated until detachment in that bandwidth.

KEYWORDS

Coffea arabica, selective detachment, selective harvesting, vibrations in coffee

1. INTRODUCTION

Colombian coffee production impacts the economy of approximately 563000 families located in more than twelve states of Colombia. It is recognized internationally for the quality associated with the aroma and taste since only ripe fruits are harvested. Given the topographical conditions of the coffee crops and market conditions, coffee harvesting is one of the most complex and expensive stages of the coffee production by the selectivity (ripe fruits) in the harvesting. Therefore, there is a great interest to study diverse techniques of harvesting ripe coffee fruits in an automated and selective method since it is difficult to have machinery in those topographic conditions. In the last decades, mechanical harvesting has played an important role in the productive chain of coffee in other countries, as for example Brazil [1]. Their production increased by including machinery in the harvesting process [2]. This was possible because Brazilian coffee permits a high percentage of green fruits as well as the plane terrains present advantages at the time of including machinery.

To stimulate a mechanical system as coffee trees efficiently, it is necessary to know the natural frequencies that characterize the system and in this way it could be possible detach only

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ripe fruits from coffee trees. The knowledge of mechanical parameters of any subsystem of the coffee tree, it will permit to describe the dynamic behavior of these and therefore understand the detachment mechanisms of the ripe fruits. The aim of this study is to evaluate numerically the detachment of coffee fruits by means of a finite element analysis. The detachment is projected from the stresses generated at the interfaces pedicel-fruit and pedicel-peduncle. A detachment model is used to verify which fruit can be detached firstly when a chirp force signal is applied on each group of fruits in the frequency interval 0-400 Hz.

2. GEOMETRIC MODEL FOR COFFEA ARABICA L. VAR. COLOMBIA FRUITS

Let´s consider that one eighth of the fruit is limited by the set of functions $f_i(t), \forall i = 1,2,3$ at the planes defined by $e_k - e_j, \forall kj = 12, 23, 31$, as observed in Figure 1a. The set $f_i(t)$ is obtained from Bezier cubic functions constructed from the points of control $P_1^{e_k-e_j}$, $P_2^{e_k-e_j}$, $P_3^{e_k-e_j}$ and $P_4^{e_k-e_j}$ established in each plane $e_k - e_j$.

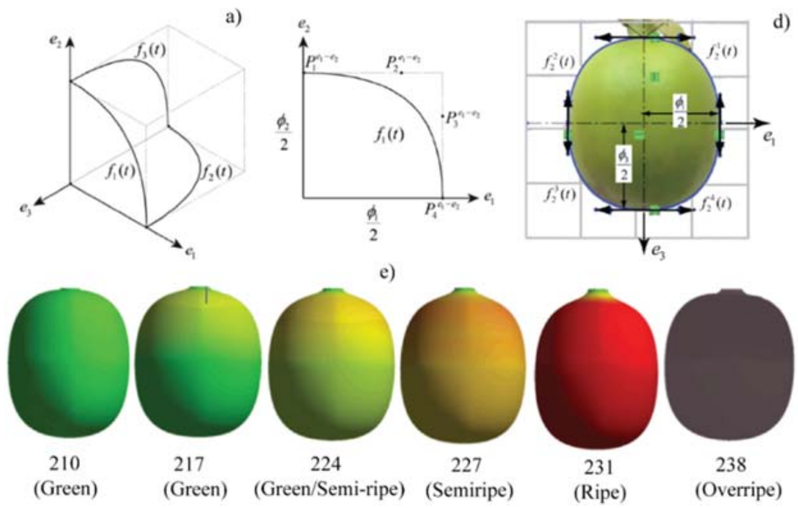

Fig. 1. a) Simple fruit model with Bezier curves [3]. b) Digital image to approximate the fruit topology. c) Fruits CAD models.

Functions that describe the form of each eighth are delimited within the following set of parametric equations

$$f_i(t) = \left\{ \left(\mathbf{X}_i(t), \mathbf{Y}_i(t) \right) \in \mathbb{R}^2 \middle| \mathbf{X}_i(t) = \mathbf{a}_i^{\mathbf{T}}\mathbf{t},\ \mathbf{Y}_i(t) = \mathbf{b}_i^{\mathbf{T}}\mathbf{t},\ \forall t \in (0,1) \right\} \tag{1}$$

where $\mathbf{a}_i^{\mathbf{T}} = [a_{1i} \quad a_{2i} \quad a_{3i} \quad a_{4i}]$, $\mathbf{b}_i^{\mathbf{T}} = [b_{1i} \quad b_{2i} \quad b_{3i} \quad b_{4i}]$ and $\mathbf{t} = \begin{bmatrix} t^3 & t^2 & t & 1 \end{bmatrix}^{\mathbf{T}}$. Each eighth of the fruit is symmetric with respect to symmetry planes. The vectors $\mathbf{a}_i$ and $\mathbf{b}_i$ are defined from the formulation of Bezier functions. The complete model can be reviewed in [3].

3. PHYSICAL-MECHANICAL PROPERTIES OF FRUIT-PEDUNCLE SYSTEM

In this section, a mathematical model will be applied to all experimental values obtained for the mechanical properties of the fruit, pedicel and peduncle. A Boltzmann Sigmoidal Model (BSE) will represent density, Poisson ratio and Young's modulus by the following equation

$$y = \frac{A_1 - A_2}{1 + e^{(x - x_0)/dx}} + A_2. \tag{1}$$

Previous studies have shown an interest for characterizing the coffee fruit and its sub-systems. Average density of coffee fruit Coffea arábica L. var. Colombia was measured by as a constant value in all ripening stages as $1.07\, g/cm^3$ [3].

For the fruit, a semi-empirical Young's modulus (E_f) was determined by [3] with a numerical iterative procedure using the firmness indices. The estimations were obtained with convergence errors less than 5 %. Coefficients values for analytical model adjusted for Young's modulus described in Equation (1) are listed in Table 1. For Coffea arábica L. var. Colombia fruit, the absolute value of Poisson's ratio was not determined. However, Poisson's ratio value is irrelevant for this study since the fruit-peduncle system acts under pendular dynamics. It means that the fruit is not subjected to considerable strain amplitudes when these are compared with strains of the structure pedicel-peduncle. In similar way as described above, Boltzmann Sigmoidal Model (BSE) was used in order to approximate the experimental data from [2] for density ρ_p, Poisson ratio ν_p and Young Modulus E_p of pedicel-peduncle of coffee Coffea arábica L. var. Colombia structures, Table 1 shows the calculated parameters of BSE for each property.

Table 1. BSE models calculated parameters for Density, Poisson´s ratio and Young Modulus for Coffea arábica L. var. Colombia structures.

Coefficients	ρ_p	ν_p	E_p	E_f
A_1	1.01	0.34	3.93	18.84
A_2	1.5	0.31	2.26	5.65
x_0	22.05	21.95	22.05	220.42
dx	0.28	0.28	0.28	1.83

4. FINITE ELEMENT HARMONIC ANALYSIS

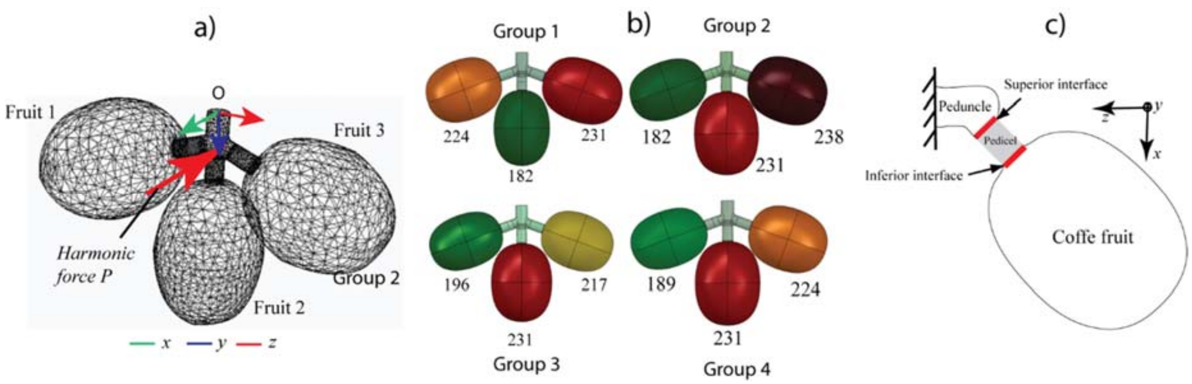

Fig. 2. Finite element mesh model for the fruit-peduncle system

A computer SONY VAIO PC (M350 2.27 GHz i3 CPU, 8 GB RAM) with Windows 7 operative system was used to perform the finite element analysis in ANSYS® Workbench 16 software. There were necessary CAD (computer aided design) models (geometric models) of each fruit in the following ripening stages: unripe 182, unripe 189, unripe 196, unripe 210, semi-ripe 224, ripe 231 and Overripe 238. For each CAD model, geometry of the pedicel was assumed cylindrical (see Figure 2) with dimensions reported by [2] for Coffea Arabica. Geometric models of glomerulus were generated using SolidWorks® software with the methodology exposed in Section 2, which was proposed by [3]. Elastic properties of fruit and peduncle-pedicel for each ripening stage were assigned using BSE approximations as described in Section 3. Applied force on the glomerulus is defined as $P = \left(0.5\hat{i} + 0\hat{j} + 0\hat{k}\right)\sin(\omega t)$ N and the application is done in a frequency range $0-400Hz$. For the harmonic stress analysis, the stresses will be determined at the interfaces of the pedicel (inferior and superior) with the stress intensity determined in the transversal cross sections highlighted in Figure 3c.

For the analysis is considered a detachment model with the aim to know which fruit will be detached of the glomerulus in the simulation. For this purpose, data reported by [4] of detachment forces in axial tension are considered as shown in Figure 3a.

The model is normalized with respect to the necessary force to detach a ripe fruit of 231 DAA. It is observed that if a glomerulus is excited mechanically; the detachment forces of non-ripe fruits should not reach 0.7 (70%) of the detachment force of a ripe fruit. The above idea is the main hypothesis used for the analysis in the four groups of fruits.

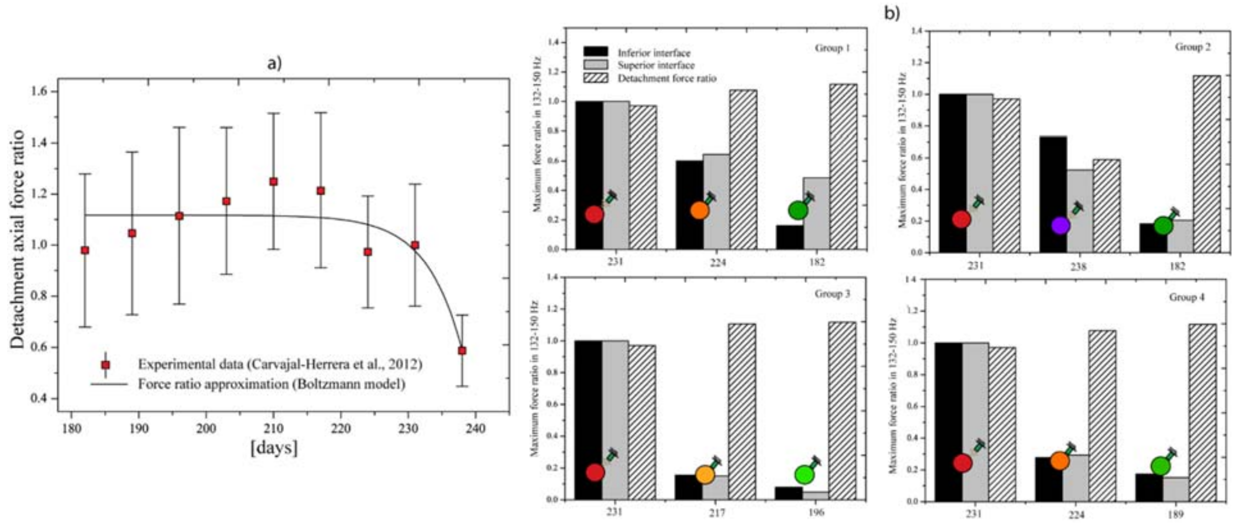

Fig. 3. a) Detachment model for the fruit. b) Results of the detachment force in the four groups of fruits in between 130-150 Hz.

5. RESULTS

To compare the stress values in the frequency with respect to the detachment model (see Figure 3b), the stress values are normalized with respect to those computed for ripe fruits such as it was done with the detachment model. In Figure 3b are shown the comparisons determined in the frequency range 130 -150 Hz. We can see that in the group 1; if the ripe fruit is detached (force ratio 1), the other fruits reach detachment force ratios between 0.2-0.65 which are not sufficient to detach those fruits according to the prescribed model in Figure 3b. In the second group of fruits, force ratio reaches 0.2 for the fruit 182 DAA and 0.78 for an over-ripe fruit 238 DAA. Results in the group 2 means that only two fruits of the group are detached (231 and 238), it indicates that the unripe fruit does not reach to detach it. The third group show that unripe fruits (196 and 217 DAA) reach ratios of 0.07-0.15, it means that when a ripe fruit is detached the forces at the interfaces reach a 15% of the detachment force of the ripe fruit. For the fourth group, force ratios achieve a range between 0.15-0.3 in the unripe fruits of 189 and 224 DAA. In all cases is demonstrated that the ripe fruits reach detachment forces in the interval 130-150 Hz and the other unripe fruits achieve a 65% which are not sufficient forces to detach the fruits according to the detachment model obtained experimentally.

CONCLUSIONS

In the study was observed that natural frequencies found in between 130-150 Hz increased the stresses at the interfaces of the ripe fruits in all groups. Results demonstrated that in all cases, the ripe fruits can be harvested selectively according to a detachment model applied. In a real context the fruit systems could be excited in frequency ranges to harvest only coffee ripe fruits, but these interval should be identified numerically (our study) or experimentally.

LITERATURE

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