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Transmissibility of coffee fruit-peduncle-branch systems submitted to vibration induced by impact

Ely Queiroz Gomes [a], Fábio Lúcio Santos [b], Moysés Nascimento [c] & Marco Antonio Zanella [d]

[a] *Faculty of Mechanical Engineering, Federal University of Uberlândia, Uberlândia, Brasil. ely_qg@hotmail.com*
[b] *Department of Engineering, Federal University of Lavras, Lavras, Brasil. fabio.santos@ufla.br*
[c] *Department of Statistic, Federal University of Viçosa, Viçosa, Brasil. moysesnascim@ufv.br*
[d] *Department of Agricultural Engineering, Federal University of Lavras, Lavras, Brasil. marco.zanella@estudante.ufla.br*

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Abstract
The development of efficient machines for coffee harvesting requires solid knowledge about the dynamic behavior of the plant. Vibration transmissibility is a parameter on dynamic behavior that may help understand this process. The aim of this study was to evaluate the average vibration transmissibility in coffee fruit-peduncle-branch samples containing unripe and ripe fruits. The experiments were performed using Arabica coffee plants of the cultivar Catuaí Vermelho. The samples were submitted to three vibration frequency levels, 20, 30 and 40 Hz, induced to the branch with impact of rigid fiberglass rods moving at a constant amplitude 2 mm. Data on acceleration were collected using an accelerometer fixed to the branch. The frequency of 20 Hz presented the highest transmissibility. Samples containing ripe fruits also presented high transmissibility when compared to those containing unripe fruits.

Keywords: mechanized harvesting, dynamic behavior, mechanical vibrations.

Transmisibilidad de los sistemas fruto-pedúnculo-ramas del café sometidos a vibración inducida por impacto

Resumen
El desarrollo de máquinas eficientes para la cosecha de café requiere un conocimiento sólido sobre el comportamiento dinámico de la planta. La transmisibilidad de la vibración es un parámetro del comportamiento dinámico que puede ayudar a comprender este proceso. El objetivo de este estudio fue evaluar la transmisibilidad de vibración promedio en muestras de rama de pedúnculo de fruta de café que contienen frutas inmaduras y maduras. Los experimentos se realizaron utilizando plantas de café Arábica "Catuaí Vermelho". Las muestras se sometieron a tres niveles de frecuencia de vibración, 20, 30 y 40 Hz, inducido a la rama con impacto de varillas rígidas de fibra de vidrio que se mueven a una amplitud constante de 2 mm. Los datos sobre la aceleración se recopilaron utilizando un acelerómetro fijado a la rama. La frecuencia de 20 Hz presentó la máxima transmisibilidad. Las muestras que contenían frutas maduras también presentaron una alta transmisibilidad en comparación con las que contenían frutas inmaduras.

Palabras clave: cosecha mecanizada, comportamiento dinámico, vibraciones mecánicas.

1. Introduction

The mechanization of agricultural activities allows greater operational efficiency and provides viability of coffee plantations, which currently depends on the reduction in production costs [4,6]. The execution of mechanized coffee harvesting with maximum efficiency reduces operational costs, as it minimizes the need for re-harvesting [10].

The harvesting of coffee fruits is one of the costliest stages in this crop [14,17]. Mechanized harvesting is considered fundamental to improve process efficiency and reduce costs. The mechanized process consists of the transfer

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of vibrational energy and impact to achieve the detachment of coffee fruits. The transfer of vibrational energy to the fruit-peduncle system depends on appropriate combinations between frequency and vibration amplitude to efficiently perform this activity [3,11,12]. The way which vibration is transmitted to coffee fruits has a direct influence on harvesting efficiency [5].

[8] studied vibration transmissibility in the grape crop by measuring the resulting accelerations directly in plants. The results demonstrated the importance of the harvester beating rods frequency in the vibrations transmitted to the plant and the consequent effects on product and plant. [1] evaluated the transmissibility and other parameters to determine the effect of fruit and leaves on the dynamic response of the citrus branch. The authors conclude that the presence of fruits on the branches reduce the values of acceleration transmissibility and the presence of leaves provides a remarkable vibration damping, as well as a modification of frequency response.

The lack of studies that incorporate the effect of the impact coming from the contact between harvester rods and the dynamic behavior of coffee stems is noteworthy, although it could make the analyses much closer to reality and contribute to the search for more efficient of mechanized harvesting systems. In this scenario, techniques based on the mechanical vibration principle can be used in the mechanized harvesting of different crops such as grape [8], coffee [2,3,5], macaw [7] and orange [1].

Therefore, the objective of this paper was to determine the average transmissibility of coffee branch containing unripe and ripe fruits, submitted to impact of rigid rods.

2. Material and Methods

The experiments were conducted using unripe and ripe fruits of Arabica coffee plants of the cultivar Catuaí Vermelho. The material was collected between March and May 2017, in the Zona da Mata region of Minas Gerais - Brazil.

The coffee samples, consisting of unripe and ripe fruit branches, were submitted to different frequency levels. For this purpose, a vibration system manufacturer by Ling Dynamic Systems (LDS) was used, powered by a PA 1000 L amplifier, a field power supply FPS 10L, a V 555M6-CE electromagnetic shaker and a Comet USB Dactron controller.

The system was controlled by an accelerometer (piezoelectric transducer) of the manufacturer PCB, with a range of 10 to 4000 Hz. The response of this accelerometer allows the precise control of the frequencies and vibration amplitudes, as configured in the management software.

The vibration was transmitted to the coffee branch by the impact of fiberglass rods. Since the samples collected in the field do not present homogeneity in relation to the diameter of the branch and arrangement of the fruits, the rods should have a regulation to allow the positioning of the samples to be evaluated. Therefore, it was necessary to design and construct a mechanical system that allowed the experiment to be carried out. The process of creation and solid modeling of the prototype was carried out in the 3D CAD software.

Samples were collected and taken to the laboratory to be prepared. First, each branch was standardized to a length of approximately 250 mm. Subsequently, the number of fruits in each sample was determined, as well as their total mass, for a better characterization. During the experiment, the samples were clamped with a mandrel, which was attached to a support base made of steel (Fig. 1).

The fixing point of the accelerometers was established at a position 10 cm away from the contact point of the rods with the branch. The accelerometers were fixed directly on the branches using self-locking plastic clips with negligible mass. To minimize the influence of the mass of the accelerometer cables in the experiment, a support was used in order to hold them. In Fig. 1, the experimental setup used during the vibration tests is presented.

The acquisition of acceleration signals from the coffee branch was performed through a National Instruments data acquisition system consisting of an NI cDAQ-9174 chassis and an NI 9234 four-channel coaxial module. The acquisition system was connected to the computer and managed by the LabView software version 14.5 (National Instruments). The acceleration data as a function of time were then processed to obtain the RMS value (Root Mean Square) of acceleration. Thus, the transmissibility of the coffee branch was calculated using Eq. 1.

$$T = \frac{a_p}{a_e}.(100) \quad (1)$$

Where,
T = transmissibility (%),
a_p = acceleration on monitored point, m.s^{-2},
a_e = excitation acceleration, m.s^{-2}.

The data corresponding to the transmissibility tests were submitted to analysis of variance, according to a completely randomized design, with eight replications. A 2 x 3 factorial scheme was used, considering two maturation stages (unripe and ripe) and three vibration frequencies (20, 30 and 40 Hz). The amplitude used was 2 mm, kept constant to avoid fruit

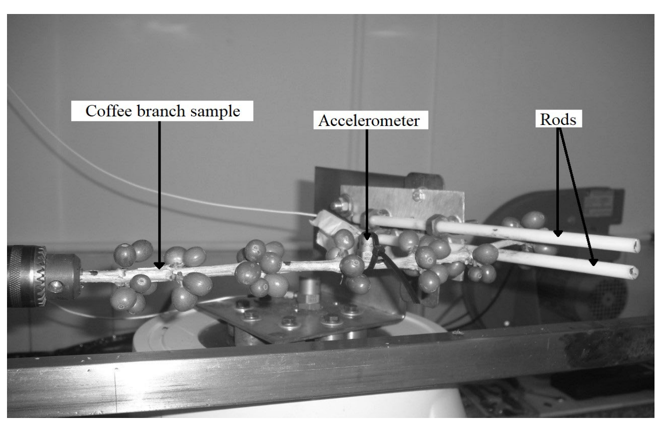

Figure 1. Experimental configuration used to perform the vibration test.
Source: The Authors.

detachment during the vibration tests, a phenomenon that would induce errors in the analysis due to sample mass alteration. The data referring to the transmissibility of the fruit-peduncle-branch systems were submitted to the Shapiro-Wilk normality test at 5% probability and presented normal distribution. Thus, the analysis of variance was performed, followed by the Tukey test at 5% probability. The averages for the qualitative factors were evaluated through the Tukey test at 5% probability. The averages for the quantitative factors were evaluated through regression analysis, in which the models were selected according to the significance of the coefficients and the coefficient of determination.

3. Results and discussion

The results of the analysis of variance at 5% probability are shown in Table 1. Frequency and maturation factors were significant, however, the interaction between them was not.

The maturation factor was significant at 5% probability. This result differs from that found by [16]. However, a different methodology for data acquisition was used by those authors, and the tests evaluated the transmissibility of the fruit-peduncle system alone. In this paper, fractions of the coffee branch were used to obtain the behavior of the fruit-peduncle-branch system. Another relevant point is the fact that the vibration is transmitted to the samples by the impact of rigid rods. These are the main differentials of this paper, which guarantees a closer proximity to the harvesting conditions in the field. In Fig. 2 are presented the results for the average transmissibility obtained at each maturation stage.

The average transmissibility obtained for ripe fruit branches was higher than for those unripe. Studying the physical properties of coffee, [3] the average fruit mass of the coffee plant was determined and, as a result, ripe fruits presented 24.64% more mass when compared to those unripe. The coffee branch does not change rigidity with variations of fruit maturation, thus, a sample with more mass will suffer greater deflection during a vibratory movement. Higher deflections imply in higher accelerations, thus ensuring greater transmissibility of vibration energy. Analyzing the average mass of the samples used in the experiment, a value of 54.7 g was obtained for ripe samples and 50.6 g for unripe samples.

It can be inferred from this result that a selective harvest would be viable in terms of vibration transmissibility. Branches containing ripe fruits transmit the initial excitation with lower energy loss and the peduncles present less rigidity, which facilitates fruit detachment [13]. However, other factors such as frequency, amplitude and form of vibration transmission are essential for obtaining the desired behavior. Fig. 3 shows the mean transmissibility values as a function of the frequency factor. This factor is widely studied in harvesting by mechanical vibration, and it is always observed as significant in the statistical analysis, which reflects its importance in the mechanized harvesting process [2,12,16].

Table 1.
Result of the analysis of variance of the transmissibility vibration as a function of frequency and maturation.

Source of variation	Degrees of freedom	Sum of squares	Mean square	F	P-values
Maturation	1	0.07	0.07	4.42	0.004*
Frequency	2	0.37	0.18	11.63	0.00*
M x F	2	0.00	0.00	0.00	0.99
Residue	42	0.68	0.02		
Total	47	1.13			

M: Maturation, F: Frequency
* - significant at 5% probability.
Source: The Authors.

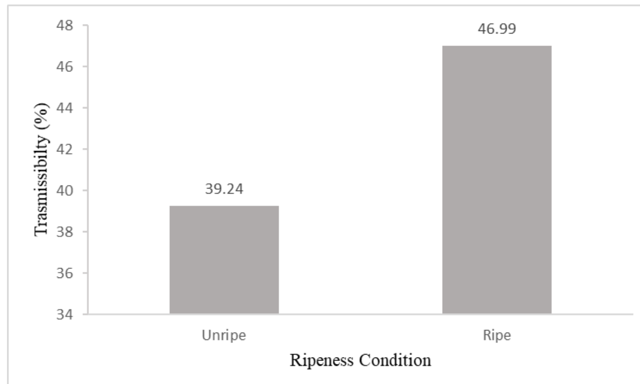

Figure 2. Mean of transmissibility values as a function of maturation (%).
Source: The Authors.

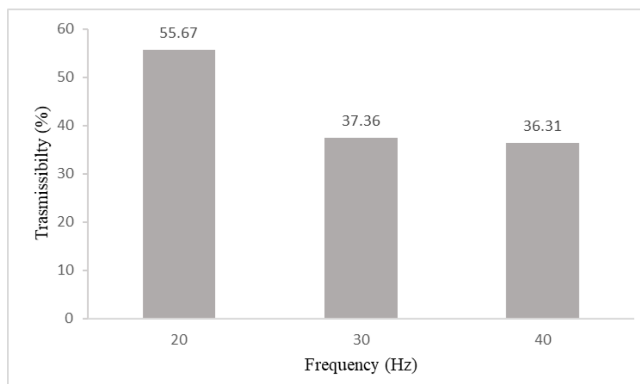

Figure 3. Average transmissibility at frequencies of 20, 30 and 40Hz.
Source: The Authors.

At a frequency of 20 Hz, the highest transmissibility was observed, exceeding the levels of 30 and 40 Hz. This behavior can be attributed to the fact that the resonance frequency of the fruit-peduncle system is close to this value. [15] indicate the frequency of 18.56 Hz and 17.01 Hz as the first natural frequency of unripe and ripe coffee fruit, respectively. [13] obtained a mean value of 23.20 Hz and 19.90 Hz for the first natural resonance frequency of unripe and ripe coffee fruits, respectively. [2] determined the natural frequency of the fruit-pedunculus system, obtaining mean values of 18.64 Hz for unripe fruits and 17.38 Hz for ripe fruits.

The results found by the authors [2,13,15] are close, and the small difference observed can be attributed to the coffee variety studied and the methodology to obtain these values. It is noteworthy again that the natural frequencies found refer to the fruit-peduncle system. However, it can be inferred that the sample response is due to the contribution of the fruit-peduncle systems excited at a frequency close to resonance, which directly interfere in the behavior of the fruit-peduncle-branch system.

The phenomenon of resonance is characterized when a physical system receives energy through frequency excitations equal to one of its natural vibration frequencies. Thus, this system starts to vibrate with increasing amplitudes [9]. This phenomenon, which is most frequently avoided in machine designs and structures, is a desirable feature when it comes to fruit detachment by vibrations. Inducing the phenomenon of resonance in the fruit-peduncle-branch system ensures a greater vibration transmissibility and, consequently, greater harvesting efficiency.

As frequency is a quantitative variable, it can be analyzed through regression analysis (Table 2). A model was determined to describe transmissibility as a function of vibration frequency.

Eq. 2 represents the linear model chosen to describe transmissibility as a function of vibration frequency. Fig. 4 shows the behavior of transmissibility as a function of vibration frequency.

$$Tr = -0.97F + 72.15 \ (\mathrm{R}^2 = 0.7906) \quad (2)$$

Where,
Tr = Vibration transmissibility (%),
F = Vibration frequency (Hz).

The linear regression analysis showed an acceptable determination coefficient of 0.79 (Fig. 4). However, when assessing transmissibility considering a higher number of frequency levels, this model will probably not be representative. This statement can be explained since the main factor of transmissibility is the excitation of the structure at frequency levels close to the natural frequency of the system, the highest values are reached when the phenomenon of resonance occurs.

4. Conclusion

Under the conditions in which the study was conducted, it can be concluded that:

- Coffee fruit-peduncle-branch samples containing ripe fruits yielded greater vibration transmissibility than those containing unripe fruits.
- The frequency of 20 Hz presented greater vibration transmissibility, surpassing the higher levels of 30 and 40 Hz.
- The highest magnitude of vibration transmissibility was obtained at a frequency close to the natural frequencies of the coffee fruit-peduncle systems.

Table 2.
Result of the analysis of variance of the transmissibility vibration as a function of frequency and maturation.

Source of variation	Degrees of freedom	Sum of squares	Mean square	F	P-value
Regression	1	0.29	0.29	18.41*	0.00
Residue	42	0.68	0.02		

* - significant at 5% probability.
Source: The Authors.

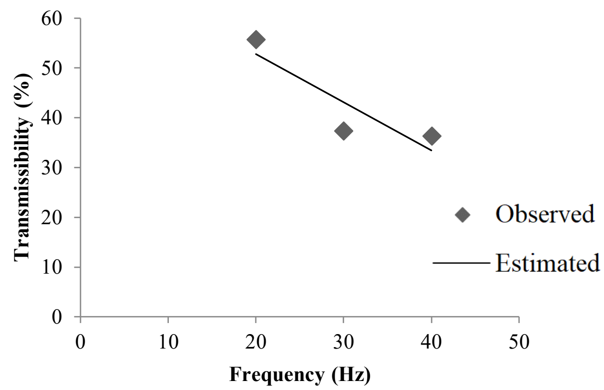

Figure 4. Linear transmissibility model as a function of frequency.
Source: The Authors.

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E.Q. Gomes, is BSc. Eng in Mechanical Engineering from the Federal University of Viçosa, Brazil (2015). MSc. in Agricultural Engineering, by the post-graduation program in Agricultural Engineering at the Federal University of Viçosa, Brazil (2017). He has experience in the area of Agricultural Engineering, with an emphasis on agricultural mechanization and machine dynamics. PhD in progress in Mechanical Engineering by the post-graduation program in Mechanical Engineering from the Federal University of Uberlândia, Brazil.
ORCID: 0000-0002-1881-2520

F.L. Santos, is BSc. Eng in Agricultural Engineering from the Federal University of Lavras, Brazil (2003), Msc. in Mechanical Engineering from the Federal University of Minas Gerais, Brazil (2005) and Dr. in Agricultural Engineering from the Federal University of Viçosa, Brazil (2008). He has experience in the areas of Agricultural Engineering and Mechanical Engineering, with an emphasis on dynamics and machine design, working mainly in the following areas: mathematical modeling, simulation, mechanical vibrations and machine design. Currently, he works as an associate professor in the Engineering Department at the Federal University of Lavras, Brazil.
ORCID: 0000-0003-1197-7338

M. Nascimento, is BSc in Statistics from the Federal University of Espírito Santo, Brazil (2007). MSc. in Applied Statistics and Biometrics from the Federal University of Viçosa, Brazil (2009). PhD in Agricultural Statistics and Experimentation from the Federal University of Lavras, Brazil (2011). He has experience in probability and applied statistics, with an emphasis on statistical methods applied to breeding - plants and animals, computational intelligence and statistical learning. He is currently an associate professor I of the Statistics Department at the Federal University of Viçosa, Brazil and CNPq Research Productivity Scholarship - Level 2.
ORCID: 0000-0001-5886-9540

M.A. Zanaella, is BSc Eng in Agricultural Engineering from the Federal University of Pelotas, Brazil (2016). Participated in the Science Without Borders program at the University of Sydney, Australia (2014). MSc. in Agricultural Engineering, by the post-graduation program in Agricultural Engineering at the Federal University of Viçosa, Brazil (2018). He has experience in the area of Agricultural Engineering, with an emphasis on agricultural mechanization and precision agriculture. PhD in progress in Agricultural Engineering at the post-graduation program in Agricultural Engineering from the Federal University of Lavras, Brazil.
ORCID: 0000-0001-7306-7976