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VIBRATION TRANSMISSIBILITY OF THE COFFEE FRUIT-PEDUNCLE SYSTEM: A FORCED VIBRATION STUDY OF HIGH FREQUENCY AIMING MECHANICAL HARVESTING

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KEYWORDS

coffee harvesting,
mechanical vibrations,
selective harvesting,
harmonic excitation.

ABSTRACT

Semi-mechanized and mechanized harvesting use machines that promote the transference of vibrational energy and impact to achieve the detachment of coffee fruits. The aim of this study was to evaluate the vibration transmissibility in coffee fruit-peduncle systems, using high-speed cameras, submitted to high frequency harmonic excitation in different combinations between frequency and amplitude of vibration, identifying working ranges suitable to perform selective harvesting. Vibration transmissibility was determined for the coffee fruit-peduncle systems, for the maturation stages unripe and ripe that were subjected to a sinusoidal harmonic displacement, in which the input parameters were frequency (35, 45 and 55 Hz) and peak-to-peak amplitude (3.5, 5.0 and 6.5 mm). An experiment was used to study the effect of frequency and amplitude on vibration transmissibility in a completely randomized design in a factorial scheme 3 x 3 x 2, with three replications. The frequency of 35 Hz, associated with the amplitudes 3.5-6.5 mm, was the one that most influenced the results of vibration transmissibility. For the frequency of 55 Hz and amplitude of 6.5 mm, in the ripe maturation stage, the vibration transmissibility was higher than 1.0, which could be a suitable combination for selective coffee harvesting.

INTRODUCTION

Brazil is the largest coffee producer in the world; this activity is one of the main pillars of agriculture in the country. In 2021, Brazilian coffee production reached 47.7 million bags (CONAB, 2021). Throughout its production cycle, coffee production demands a considerable number of operations, which significantly influence the final costs of the product (Almeida & Zylbersztajn, 2017). Additionally, coffee is a product whose price is associated with quality parameters and so harvesting is an important process in the production chain, to obtain a product with a great quality (Santos et al., 2010a, Santos et al., 2010b, Silva et al., 2015).

Coffee harvesting can be manual, semi-mechanized or mechanized. Semi-mechanized and mechanized harvesting use machines that promote the detachment of fruits through mechanical vibrations (Tavares et al., 2019; Santos et al., 2010a, Santos et al., 2010b, Santos, et al., 2015, Silva et al., 2015, Gomes et al., 2016). In this context, the comprehension of the dynamic behavior of the plant during the harvesting process is very important. Therefore, studies about the axial forces for detachment of the fruits (Silva et al., 2016; Ferreira Júnior et al., 2018), resonant frequencies of the fruit-peduncle and fruit-peduncle-branch system, the determination of the frequency and amplitude factors during the harvesting process and the vibration transmissibility to the fruit-peduncle system, can contribute to increasing the efficiency of the process (Santos et al., 2010a, Santos et al., 2010b, Villibor et al., 2019).

Mechanized harvesting of coffee fruits combines the transference of mechanical energy and impact to achieve the detachment of coffee fruits (Gomes et al.,

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2016; Villibor et al., 2019). The transference of mechanical energy to the fruit-peduncle system depends on suitable combinations between frequency and amplitude of vibration, in order to perform the detachment with efficiency and selectivity. The selective harvesting of coffee fruits is mainly influenced by the lack of uniformity in the maturation stage of the coffee fruits in the plants. In addition, this lack of uniformity interferes on the decision of the ideal moment to start the harvesting (Silva et al., 2015) and it becomes difficult to define combinations between the frequency and amplitude of vibration imposed by the harvester machines.

When the plant is submitted to the forced vibrations, the response of the coffee fruit-peduncle system, due to dynamic efforts, becomes more complex. The transmissibility of vibration is a parameter that can help to understand the behavior of the system and indicate suitable working ranges, to achieve selectivity during coffee harvesting. The transmissibility of vibration has been studied to improve the performance of machine-plant interaction (Pezzy & Caprara, 2009; Savary et al., 2011, Souza et al., 2018). Information about the transmissibility of vibration between the harvesting device and the plant is scarce, especially for the coffee fruit-peduncle system. The evaluation of accelerations and displacements presents several complications, such as the difficulty of using transducers directly in the systems, due to the fact that the increased mass can interfere in its dynamic response (Beberniss & Ehrhardt, 2017).

High-speed cameras and digital image processing techniques can be employed to determine the transmissibility of vibration to the coffee fruit-peduncle system during the harvesting process by mechanical vibrations. The use of high speed cameras allows the study of the dynamic behavior of mechanical systems without direct contact between the sensor element and the system to be studied. Furthermore, this kind of system enables the monitoring of multiple points at the same time (Durand-Texte et al., 2020, Villibor et al., 2016, Villibor et al., 2019). The cited authors emphasized that it was possible to estimate the displacements at high frequencies using digital cameras with high resolution and high sampling rates.

Therefore, considering the importance of studying the transmissibility of vibration from the harvesting devices to the coffee fruit-peduncle system, which can be performed using high-speed digital cameras and image processing techniques. The aim of this study was to evaluate the transmissibility of vibration in coffee fruit-peduncle systems subject to high frequency harmonic excitation in different combinations of frequency and amplitude of vibration, and to identify the working ranges suitable for performing selective harvesting.

MATERIAL AND METHODS

Laboratory tests were carried out to determine the vibration transmissibility in harmonically excited coffee fruit-peduncle systems. Samples of the Catuaí Vermelho coffee variety were collected in an experimental area and tested. The coffee samples were visually classified, considering ripe and unripe maturation stages.

The transmissibility of vibration (Rao, 2008) was determined for the transverse direction to the movement of the shaker base (Tx) and for the direction of the input displacement (Ty), which are relative to the reference axes x and y, respectively (Equations 1 and 2). For this purpose, the displacement of the shaker (amplitude of the input displacement) and the displacement of the free end of the coffee fruit (amplitude of the response displacement) were determined.

$$Tx = \frac{X_s}{Y_{in}} \tag{1}$$

$$Ty = \frac{Y_s}{Y_{in}} \tag{2}$$

in which:

Tx - displacement transmissibility in x direction;

Ty - displacement transmissibility in y direction;

X_s - displacement of the coffee fruit free end in the x direction, mm;

Y_s - displacement of the coffee fruit free end in the y direction, mm,

Y_{in} - input displacement on the shaker base, mm.

Table 1 presents the input parameters, frequency and amplitude of vibration, used to determine the vibration transmissibility of coffee fruit-peduncle systems, in ripe and unripe stages of maturation. In commercial coffee harvesters, a working frequency of 25 Hz is commonly used. However, in this study, sinusoidal harmonic excitation was considered as an input displacement for higher frequencies (35-55 Hz). The association of higher frequencies and reduced amplitudes was used in order to increase the number of loading cycles imposed on the system during the harvesting process.

TABLE 1. Frequencies and amplitudes of vibration used to determine the transmissibility of vibration to the coffee fruit-peduncle systems.

Input parameters	
Frequency (Hz)	35, 45 and 55
Peak-to-peak amplitude (mm)	3.5, 5.0 and 6.5

The input energy per vibration cycle, applied to the coffee fruit-peduncle system, was controlled by an electromagnetic shaker. The instrumentation used was manufactured by Ling Dynamic Systems (LDS) and comprised a COMET$_{\mathrm{USB}}$ signal generator, a PA100E-CE signal amplifier and a model V406 shaker. The main features of the instrumentation were: dynamic range from 5 to 9000 Hz; maximum load of 198 N; maximum peak-to-peak displacement of 17.6 mm; and maximum acceleration of 100 g. The controlling and monitoring of the displacement of the shaker were performed by using a piezoelectric transducer produced by PCB (model 353B33), with a working range from 1 to 4 kHz.

Table 2 shows the input energy per vibration cycle for the frequency and amplitude combinations used in this study. The amount of energy transferred to coffee fruit-peduncle systems depends on the damping of the system and the vibration transmissibility.

TABLE 2. Energy per input cycle imposed on coffee fruit-peduncle systems during the vibration tests for each combination of frequency and amplitude of vibration.

Frequency (Hz)	Amplitude (mm)	Energy (J kg^{-1})
35.0	3.5	0.5924
35.0	5.0	1.2090
35.0	6.5	2.0433
45.0	3.5	0.9793
45.0	5.0	1.9986
45.0	6.5	3.3776
55.0	3.5	1.4629
55.0	5.0	2.9856
55.0	6.5	5.0456

Samples of plagiotropic branches of coffee, with a length of 0.05 m and containing only one fruit per stem, were attached to the mobile base of the electromagnetic shaker and submitted to a sinusoidal harmonic displacement, $Y(t) = A\sin(\omega t)$, whose time (t), frequency (ω) and amplitude (A) parameters were configured using a system specific program.

For displacement monitoring of the free end of the coffee fruit, high-speed videos were used. A model Exilim EX-FH20 Casio digital camera was used to capture videos at the following sampling rates: 420 and 1000 Hz. For each sampling rate, the camera was configured to the respective resolutions: 480 x 224, 224 x 168 and 224 x 80 pixels. The lighting was kept constant during the acquisition of all videos. The experimental set up during the vibration tests, considering the reference axes, the displacement direction and the positioning of the camera are shown in Figure 1.

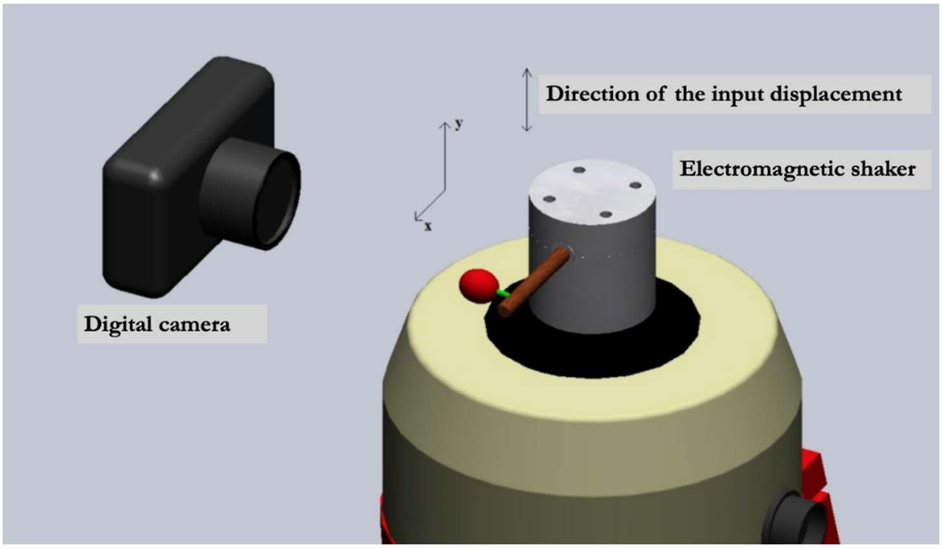


FIGURE 1. Representation of the experimental set up: electromagnetic shaker, reference axes and the direction of the input displacement.

Sampling rates were selected according to the Nyquist theorem (Xiao & Xiang-Gen, 2018). However, when the waveform is desirable, the sampling rate should be approximately 10 times the frequency presented in the signal (National Instruments, 2020) (Table 3).

TABLE 3. Sampling rates used during the vibration tests for monitoring the higher frequencies evaluated.

Excitation (Hz)	Sampling rate (Hz)
35.0	420
45.0	1000
55.0	1000

During the vibration tests, to determine the displacements of the fruit-peduncle system, the methodology proposed by Villibor et al. (2016) was used. Thus, a black background image was employed, associated with four control points. The original videos acquired were composed of a sequence of color images in the RGB standard, at a resolution associated with the video sampling rate.

The image segmentation process was carried out by means of a thresholding operation (Gonzalez & Woods, 2018). A gray level was defined in a specific band, to segment the monitoring and reference points of the rest of the image. The segmentation threshold, used in all images, was determined manually from the first segmented image.

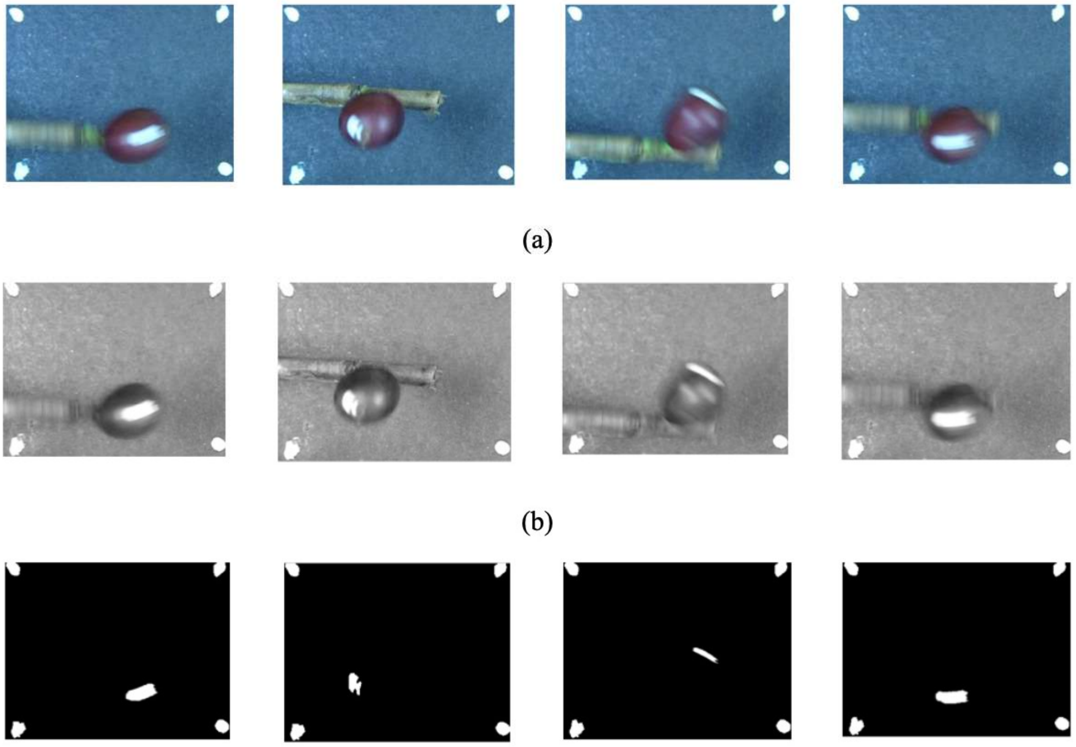
All objects present in the binary image were identified, i.e. the control points, monitoring points and noise objects. Noise objects, with a smaller influence area than the areas of the regions of interest, were manually eliminated. Subsequently, a matrix of the results was determined, composed of the coordinates of each object of interest. A transformation of coordinates was carried out between the control and monitoring points, based on the equations proposed by Segerlind (1984), to determine the displacements of the free end of the fruit (mm). The resulting displacements for coffee fruit-peduncle systems were determined and these allowed an evaluation of the predominant mode shapes in the system.

For the coffee fruit-peduncle systems, the effect of frequency, amplitude and maturation stage (Table 1) on the transmissibility of vibration in the x and y directions (Tx and Ty), was evaluated from an experiment in a completely randomized design, in a 3 x 3 x 2 factorial scheme (frequencies of vibration x amplitudes of vibration x maturation stages), with three replications, totaling 54 experimental units. First of all, the study was carried out by considering all the input factors and then, later, considering the effects of the frequency and amplitude of vibration at each stage of maturation.

For each maturation stage, considering the frequency and amplitude of vibration, the transmissibility was studied by means of regression analysis. The models were selected based on the significance of the estimated parameters, using the t-test. A significance level of 10% was defined in all analyses, considering the high variability inherent in coffee culture.

RESULTS AND DISCUSSION

Figure 2 illustrates the results obtained after the processing of the videos for a coffee fruit-peduncle system, in ripe maturation stage. Similar results were obtained for all of the sampling rates adopted (Table 3), except for the threshold used in the image segmentation process and the resulting spatial resolution.



(a)

(b)

(c)

FIGURE 2. Results obtained from the video processing for the coffee fruit-peduncle system in ripe maturation stage (a) RGB, (b) gray scale and (c) binary images.

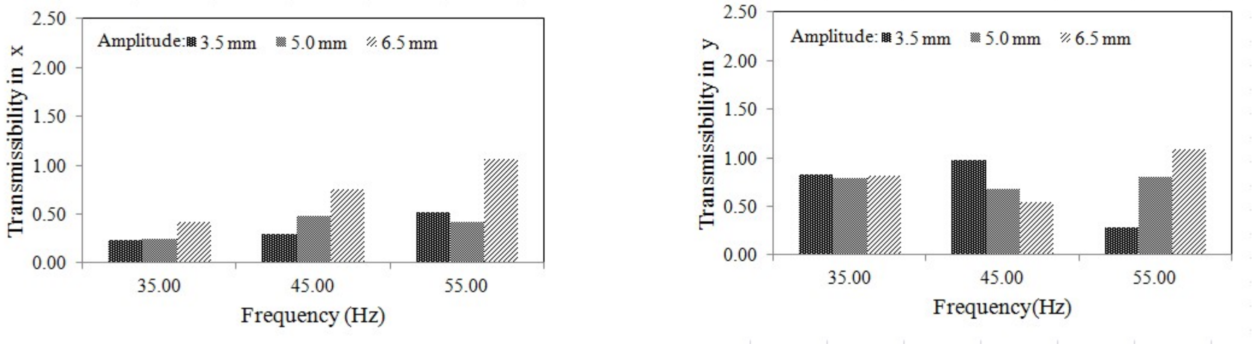
Table 4 presents the spatial resolutions achieved for the sampling rates considered in this study. It was observed that, from the proposed configuration, it is possible to determine the displacements of the coffee fruit, since the smallest amplitude at the free end of the fruit was 1.05 mm.

TABLE 4. Spatial resolution achieved for the sampling rates of 420 and 1000 Hz.

Sampling rate (Hz)	Spatial resolution (mm/pixel)
420	347
1000	818

From the results of the variance analysis, it was found that the studied factors (vibration frequencies, vibration amplitudes and maturation stages) did not present significant differences for the vibration transmissibility in the x and y directions. These results can be explained by the high variability among the coffee samples collected, which presented a variation coefficient of 462.73% and 87.70%, respectively.

The averages of Tx and Ty, for the ripe maturation stage, are presented for each of the treatments in Figure 3.

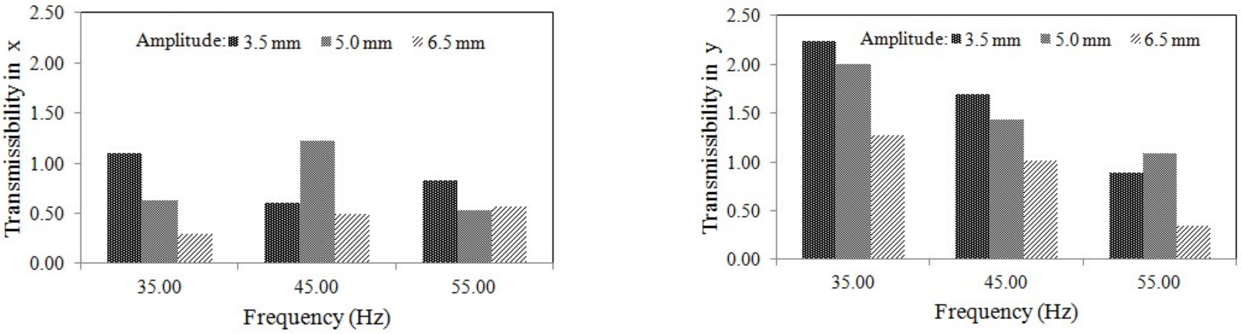


(a) (b)

FIGURE 3. Average vibration transmissibility observed for the coffee fruit-peduncle system, in x (a) and y (b) directions, for the ripe maturation stage.

The highest values for Tx and Ty, equal to 1.10 and 1.07, were observed at a frequency of 55 Hz and an amplitude of 6.5 mm. For these transmissibility values, the displacements observed at the free end of the coffee fruit were 7.15 and 6.96 mm (Figure 3).

The averages of Tx and Ty, for the unripe maturation stage, are presented for each of the treatments in Figure 4.



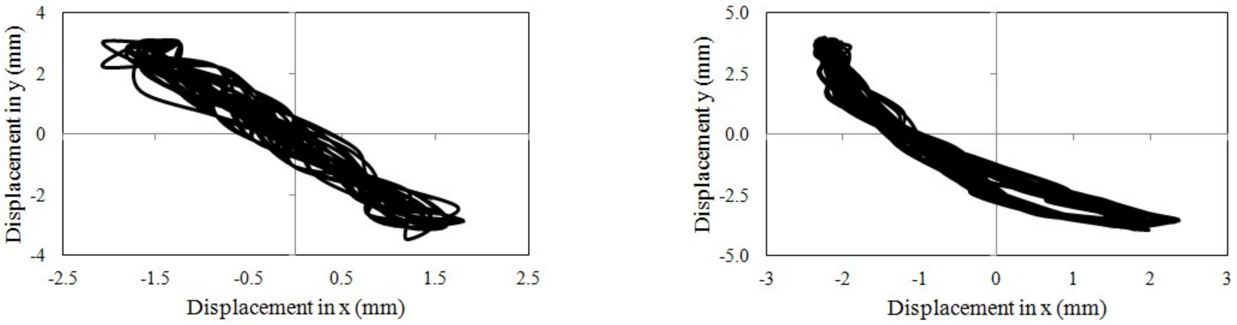
(a) (b)

FIGURE 4. Average vibration transmissibility observed for the coffee fruit-peduncle system in x (a) and y (b) directions, for the unripe maturation stage.

The transmissibility in the x direction was 1.10 for the frequency of 35 Hz, associated with an amplitude of 3.5 mm, and 1.23 for the frequency of 45 Hz and amplitude of 5 mm. For the transmissibility of vibration above 1.00, the resulting displacements at the free end of the fruit were 3.85 and 6.15 mm. The highest value of the vibration transmissibility in the y direction was 2.24 for a frequency of 35 Hz associated with amplitude of 3.5 mm. The largest output displacement, equal to 10.05, was observed for a frequency of 35 Hz and amplitude of 5.0 mm (Figure 4).

Santos et al. (2015) estimated the natural frequencies associated with the torsional mode shape at 50.37 and 57.66 Hz for the ripe and unripe maturation stages, respectively. If the coffee fruit-peduncle system vibrates in torsional mode, smaller displacements in the x and y directions are expected, since the angular displacements around the stem would be predominant.

Figure 5 represents the resulting displacements, for a frequency of 55 Hz and amplitude of 5 mm, for the coffee fruit-peduncle system in the ripe and unripe maturation stages.



(a) (b)

FIGURE 5. Resulting displacement for the coffee fruit-peduncle system, in the ripe (a) and unripe (b) maturation stages, for a frequency of 55 Hz and amplitude of 5 mm.

It can be observed that the resulting displacement at this frequency differs from low frequencies and the displacements in the x direction are not expressive. This vibration pattern was verified for 60.8% of the samples (Figure 5). The pendular displacement is less pronounced in samples excited in frequencies associated with the torsional mode shape (Tinoco et al., 2014, Santos et al., 2015).

The influence of the frequency and amplitude of vibration on Tx was observed for the ripe maturation stage. The proposed model can be considered suitable, since regression was significant and a lack of fit was non-significant at 10% probability. The determination coefficient for the model was 73.16% and the data variation coefficient was 47.03%. The combination of frequency and amplitude directly affects the dynamic response of the fruit-peduncle system, being fundamental to increasing the efficiency of mechanized coffee harvesting by mechanical vibrations (Santos et al., 2010b, Tinoco et al., 2014, Santos et al., 2015, Gomes et al., 2016, Tinoco & Peña, 2018, Villibor et al., 2019).

For the transmissibility Tx, the significance of the estimated parameters was investigated using the t test. It was observed that, with an increase in frequency and amplitude of vibration, there is an increase in the vibration transmissibility to the coffee fruit-peduncle system in a transverse direction to the input displacement, as presented in Figure 6. Equation (3) represents the fitted response surface for the vibration transmissibility in the x direction, for the coffee fruit-peduncle system in the ripe maturation stage.

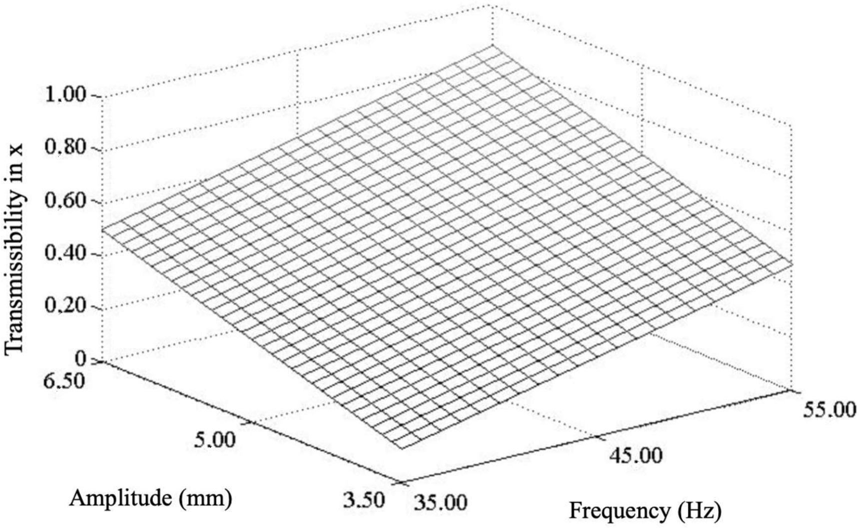
$$Tx = -0.90859 - 0.01723F - 0.12336A \tag{3}$$

in which:

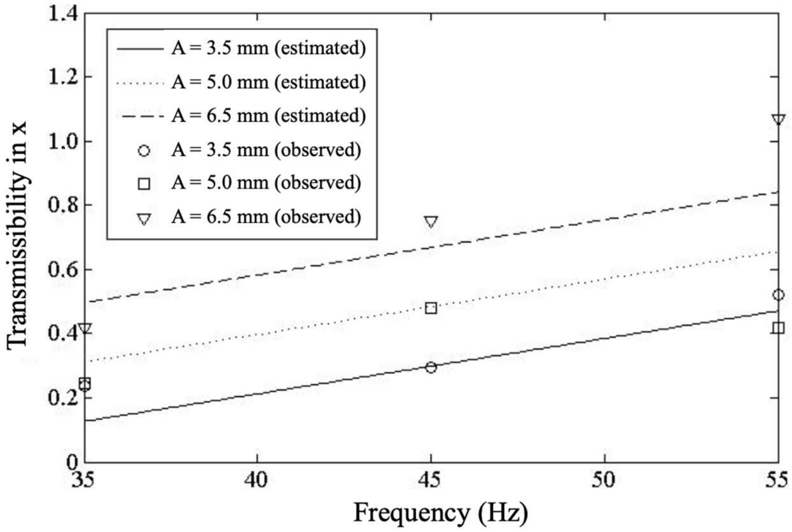
Tx - transmissibility in x direction (ripe maturation stage);

F - frequency, Hz,

A - amplitude, mm.



(a)



(b)

FIGURE 6. Fitted response surface for the vibration transmissibility in the x direction, for the coffee fruit-peduncle system in the ripe maturation stage (a). Vibration transmissibility in the x direction, estimated and observed for the vibration amplitudes (b).

Figure 6(a) presents the response surface from the fitted model representing the transmissibility of vibration in the x direction, for the coffee fruit-peduncle system in the ripe maturation stage. It can be observed that, regardless of the input frequency and amplitude, the vibration transmissibility was below 1.00. The average vibration transmissibility was 0.47 and the highest, estimated by the model, was 0.84 (for a frequency of 55 Hz and amplitude of 6.5 mm). Figure 6(b) represents the vibration transmissibility as a function of amplitude, highlighting the relation between these factors on the vibration transmissibility and, consequently, on harvesting efficiency (Santos et al., 2010a, Santos et al., 2010b). The vibrational energy transmitted to the coffee fruit-peduncle system is greater when these two factors are increased (Villibor et al., 2019) for the vibration transmissibility in the x-axis.

It was observed that Ty was significantly influenced by the interactions between frequency and amplitude of vibration (Figure 7). Equation 4 represents the fitted response surface for Ty as a function of vibration frequencies and amplitudes in the ripe maturation stage.

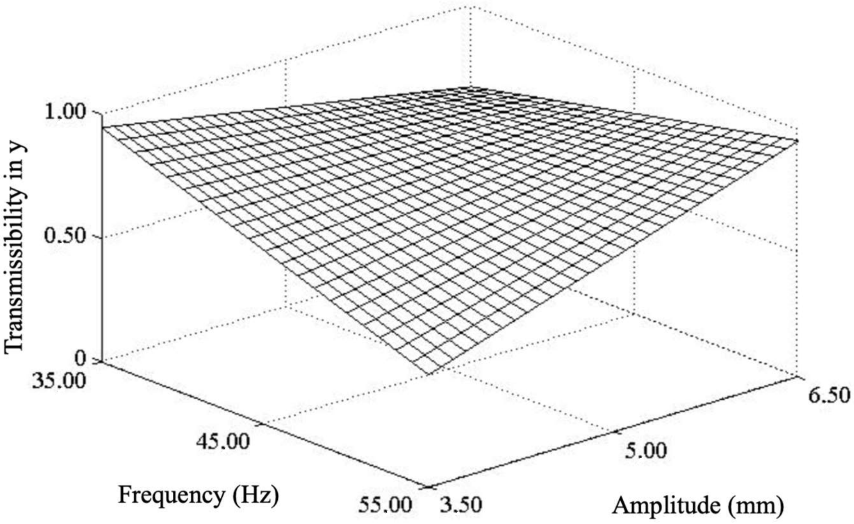
$$Ty = 3.7338 - 0.07020F - 0.54943A + 0.0130FA \quad (4)$$

in which:

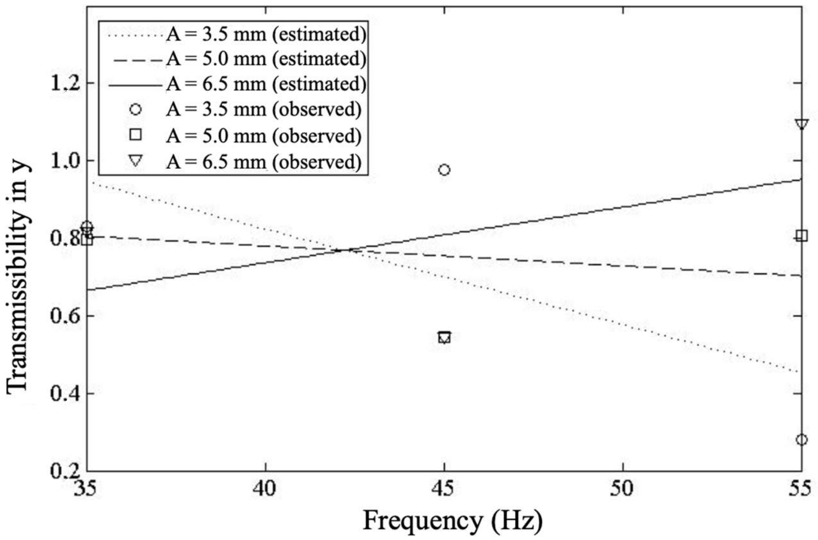
Ty - transmissibility in y direction (ripe maturation stage);

F - frequency, Hz;

A - amplitude, mm.



(a)



(b)

FIGURE 7. Fitted response surface for Ty as a function of vibration frequencies and amplitudes in the ripe maturation stage (a) and vibration transmissibility as a function of frequency for each of the amplitudes studied (b).

The fitted response surface is shown in Figure 7(a). This result suggests atypical behavior for the transmission of vibrations, since both extremes of the amplitudes and frequencies studied (35 Hz and 3.5 mm and 55 Hz and 6.5 mm) presented the highest estimated values, close to 0.95. The lowest vibration transmissibility in the y direction (below 0.5) was observed for the frequency 55 Hz and amplitude of 3.5 mm. Figure 7(b) represents the vibration transmissibility as a function of amplitude, regardless of the amplitude considered; the experimental results were very similar. This behavior was not verified for the frequencies of 45 and 55 Hz. These results indicate that the effect of frequency on the vibration transmissibility depends on the amplitude imposed on the coffee fruit-peduncle system, and these factors cannot be worked separately. Such behavior corroborates the results available in the literature, in which coffee harvesting efficiency is significantly influenced by the frequency and amplitude of vibration (Santos et al., 2010a, Santos et al., 2010b, Gomes et al., 2016). When analyzing the vibration transmissibility in the y directions, the frequency of 55 Hz and the amplitude of 6.5 mm provided greater output displacements (Figure 8). With greater displacements in the system, there are greater deformations in the fruit-peduncle connections, as well as the connection between the stem and the branch, which can contribute to fruit detachment (Santos et al., 2015).

Only the amplitude of vibration had a significant effect on the vibration transmissibility in the x direction at the unripe maturation stage (Figure 8). The lack of fit was not significant, indicating that the model is suitable for explaining the variation in Tx as a function of the amplitude (Equation 5). It was observed that the determination coefficient is 31.16%, which is considered to be low. The highest Tx was observed for a frequency of 45 Hz and amplitude of 5 mm.

$$Tx = 1.35828 - 0.13179A \tag{5}$$

in which:

Tx - transmissibility in the x direction (unripe maturation stage);

A - amplitude, mm.

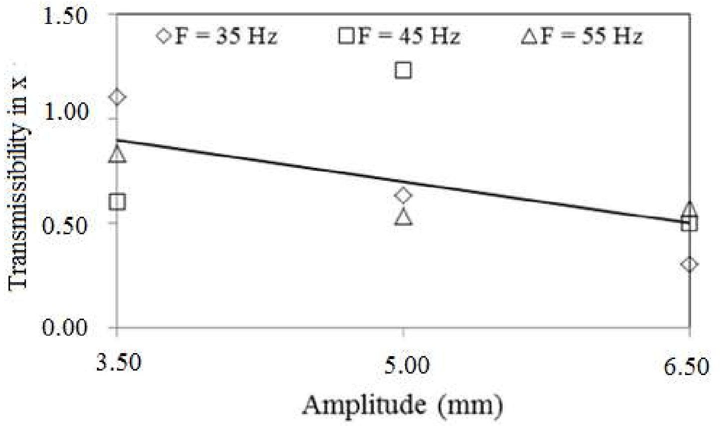


FIGURE 8. Vibration transmissibility in the x direction (Tx) as a function of the vibration amplitudes (3.5, 5.0 and 6.5 mm) in the unripe maturation stage.

For Ty in the unripe maturation stage, the fitted model's frequency and amplitude had a significant effect on the vibration transmissibility, as observed in the literature, and these factors can influence the fruit detachment efficiency at this stage of maturation (Santos et al., 2010a, Santos et al., 2010b, Gomes et al., 2016), as presented in Figure 9. The model's lack of fit was not significant, which demonstrates that it is suitable to represent Ty, with a determination coefficient of 89.66% (Equation 6).

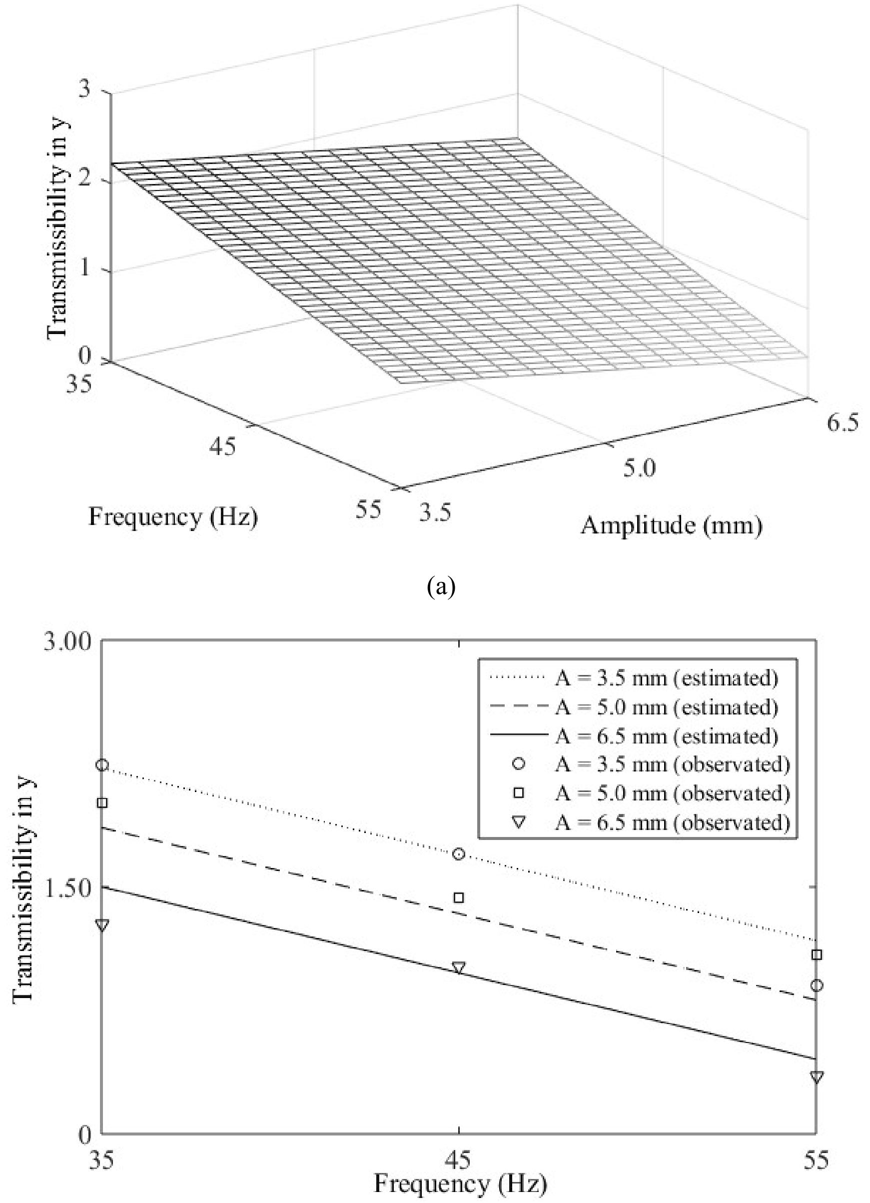
$$Ty = -4.89307 - 0.05237F - 0.23986A \qquad (6)$$

in which:

Ty - transmissibility in the y direction (unripe maturation stage);

F - frequency, Hz;

A - amplitude, mm.



(a)

(b)

FIGURE 9. Fitted response surface for Ty as a function of vibration frequencies and amplitudes in the unripe maturation stage (a) and vibration transmissibility as a function of frequency for each of the amplitudes studied (b).

The response surface for Ty, at the unripe maturation stage, is shown in Figure 9(a). It can be seen that Ty tends to decrease with an increase of the frequency of vibration. It should be noted that, the frequency of 55 Hz is close to the natural frequency relative to the torsional mode, estimated by Santos et al. (2015) at 57.66 Hz for the unripe maturation stage. In this way, angular displacements around the stem would be more expressive than the translational displacements; however, its experimental determination becomes more difficult. Figure 9(b) shows vibrating transmissibility in the y direction (Ty), as a function of the studied amplitudes. It can be seen that the fitted model is suitable due to the low dispersion of the observed data in relation to the fitted data.

Comparing the vibration transmissibility between the ripe and unripe maturation stages, it was noted that the unripe stage presented higher values than the ripe stage, considering the studied frequency and amplitude levels.

For the ripe maturation stage, vibration transmissibility higher than 1.00 was not observed for the x or y directions. These results can be related to the damping of the coffee fruit-peduncle system on the different maturation stages. According to Villibor et al. (2016), the damping coefficients of the fruit-peduncle systems for the ripe maturation stage are higher when compared to the unripe ones. Thus, as higher the damping of the system, higher the energy dissipation during the mechanical vibration process (Meirovitch, 2001).

CONCLUSIONS

From the results obtained, it can be concluded that:

- The use of high-speed videos allows the determination of the displacements resulting from the coffee fruit-peduncle system when submitted to harmonic excitation;

- The frequency of 35 Hz, associated with amplitudes from 3.5-6.5 mm, was the one that most influenced the results of vibration transmissibility for both directions studied, with significant differences between the unripe and ripe maturation stages;

- For the frequency of 55 Hz and amplitude of 6.5 mm in the ripe maturation stage, the vibration transmissibility was higher than 1.0, meanwhile, for the unripe maturation stage, this combination presented the lowest vibration transmissibility values, which could be a suitable combination for selective coffee harvesting.

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REFERENCES

Almeida LF, Zylbersztajn D (2017) Key success factors in the Brazilian Coffee Agrichain: present and future challenges. Journal on Food System Dynamics 8(1):45-53. DOI: http://dx.doi.org/10.18461/ijfsd.v8i1.814.

Beberniss TJ, Ehrhardt DA (2017) High-speed 3D digital image correlation vibration measurement: Recent advancements and noted limitations. Mechanical Systems and Signal Processing 86(B):35-48. DOI: https://doi.org/10.1016/j.ymssp.2016.04.014.

CONAB - Companhia Nacional de Abastecimento (2021) Acompanhamento da safra brasileira: Café, 5(4), Safra 2021 Quarto levantamento, dezembro/ 2021. Available: http://www.conab.gov.br/. Accessed Jul 04, 2022.

Durand-Texte T, Melon M, Simonetto E, Durand S, Moule M (2020) Single-camera single-axis vision method applied to measure vibrations. Journal of Sound and Vibration 465 (115012):1-12. DOI: https://doi.org/10.1016/j.jsv.2019.115012.

Ferreira Júnior LG, Silva FM, Ferreira DD, Simão SD, Souza GC, Ferreira LK (2018) Characterization of the coffee fruit detachment force in crop subjected to mechanized harvesting. Coffee Science 13(1):71-79. DOI: https://doi.org/10.25186/cs.v13i1.1379.

Gomes EQ, Santos FL, Jesus VAM (2016) Influence of the impact of a rigid rod on the coffee fruits detachment by mechanical vibrations. Agrarian 9(32):172-181.

Gonzalez R, Woods R (2018) Digital image processing. Pearson. 580p.

Meirovitch L (2001) Fundamental of Vibrations. New York, McGraw Hill. 799p.

National Instruments (2020) Aquisição de sinais analógicos: largura de banda, teorema de amostragem de Nyquist e aliasing, NI Documentation 2020. Available: https://www.ni.com/pt-br/innovations/white-papers/06/acquiring-an-analog-signal--bandwidth--nyquist-sampling-theorem-.html. Accessed Jun 20.

Pezzy F, Caprara C (2009) Mechanical grape harvesting: Investigation of the transmission of vibrations. Biosystems Engineering 1(3):281-286. DOI: https://doi.org/10.1016/j.biosystemseng.2009.04.002.

Rao SS (2008) Vibrações mecânicas. São Paulo, Pearson Universidades. 448p.

Santos FL, Queiroz DM, Pinto FAC, Resende RC (2010a) Efeito da frequência e amplitude de vibração sobre a derriça de frutos de café. Revista Brasileira de Engenharia Agrícola e Ambiental 14(4): 425-431.

Santos FL, Queiroz DM, Pinto FAC, Santos NT (2010b) Analysis of the coffee harvesting process using an electromagnetic shaker. Acta Scientiarum. Agronomy 32(3):373-378. DOI: https://doi.org/10.4025/actasciagron.v32i3.6782.

Santos FL, Queiroz DM, Valente DSM, Coelho ALF (2015) Simulation of the dynamic behavior of the coffee fruit-stem system using finite element method. Acta Scientiarum. Technology 37(1):11-17. DOI: https://doi.org/10.4025/actascitechnol.v37i1.19814.

Savary SKJU, Ehsani R, Salyani M, Hebel MA, Bora GC (2011) Study of force distribution in the citrus tree canopy during harvest using a continuous canopy shaker. Computers and Electronics in Agriculture 76(1):51-58. DOI: https://doi.org/10.1016/j.compag.2011.01.005.

Segerlind LJ (1984) Applied finite element analysis. New York, John Wiley & Sons. 427p.

Silva FC, Silva FM, Alves MC, Ferraz GAS, Sales RS (2015) Efficiency of coffee mechanical and selective harvesting in different vibration during harvest time. Coffee Science 10(1):56-64.

Silva FC, Silva FM, Scalco MS, Sales RS (2016) Correlação da Força de Desprendimento dos Frutos em Cafeeiros sob Diferentes Condições Nutricionais. Coffee Science 11(2):169-179.

Souza, VHS, Santos, AAR, Costa, ALG, Santos, FL, Magalhães, RR (2018) Evaluation of the interaction between a harvester rod and a coffee branch based on finite element analysis. Computers and Electronics in Agriculture 150:476-483. DOI: https://doi.org/10.1016/j.compag.2018.05.020.

Tavares TO, Oliveira BR, Silva VA, Silva RP, Santos AF, Okida ES (2019) The times, movements and operational efficiency of mechanized coffee harvesting in sloped areas. Plos One 14(5): 1-10. DOI: https://doi.org/10.1371/journal.pone.0217286.

Tinoco HA, Ocampo DA, Peña FM, Sanz-Uribe JR (2014) Finite element modal analysis of the fruit-peduncle of Coffea Arabica L. var. Colombia estimating its geometrical and mechanical properties. Computers and Electronics in Agriculture 108(1):17-27. DOI: https://doi.org/10.1016/j.compag.2014.06.011.

Tinoco HA, Peña FM (2018) Harmonic stress analysis on Coffea Arabica L. Var. Colombia fruits in order to simulate the selective detachment: A finite element analysis. Simulation 94(2):163-174. DOI: https://doi.org/10.1177/0037549717738068.

Villibor GP, Santos FL, Queiroz DM, Khoury Junior JK, Pinto FAC (2016) Determination of modal properties of the coffee fruit-stem system using high speed digital video and digital image processing. Acta Scientiarum Technology 38(1):4-48. DOI: https://doi.org/10.4025/actascitechnol.v38i1.27344.

Villibor GP, Santos FL, Queiroz DM, Khoury Junior JK, Pinto FAC (2019) Dynamic behavior of coffee fruit-stem system using modeling of flexible bodies. Computers and Electronics in Agriculture 166(1):1-8. DOI: https://doi.org/10.1016/j.compag.2019.105009.

Xiao L, Xiang-Gen X (2018) Frequency determination from truly sub-Nyquist samplers based on robust Chinese remainder theorem. Signal Processing 150:248-258. DOI: https://doi.org/10.1016/j.sigpro.2018.04.022.