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Dynamic behavior of coffee tree branches during mechanical harvest

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ABSTRACT

The coffee industry stands out worldwide due to its socioeconomic importance, acting directly or indirectly in the most diverse sectors. With this, new technologies and several harvester models have emerged. These harvesters have regulations that can influence the efficiency of harvesting, the selectivity of fruits and the preservation of the crop. In this way, the understanding of the behavior of harvester components and their dynamic relationship with coffee are essential for mechanical harvesting management and for developing new products. The objective of this work was to obtain the coffee tree branch displacement (in terms of frequency and amplitude of vibration) through instrumentation and signal processing techniques. For this, a low cost system was developed, consisting of an Arduino open source electronic prototyping platform and an accelerometer. The acceleration signals were collected and processed via MatLab. The results showed the complete two-dimensional displacement performed by the coffee tree branches for different harvester settings during the mechanical coffee harvesting. From the vibration displacements of the branches it is possible to unveil the dynamic interaction between machine and coffee tree, contributing to the management of mechanical coffee harvesting and to the development of new vibration harvesting systems.

1. Introduction

Coffee mechanization has led to the emergence of new Technologies and various harvester models, favoring cost reductions during the harvesting process and, consequently, making the coffee grower more competitive in the agricultural Market.

The mechanization of cultivation and harvesting operations assumes a role that has been giving breath to coffee farmers in times of crisis by reducing operating costs (Oliveira et al., 2007a, 2007b).

According to Ferraz (2012) coffee harvesting is more difficult to study than crops such as cereals due to characteristics such as plant shape, uneven fruit ripeness and high moisture content. They also states that besides being a perennial shrub, each coffee plant can have different shape, with differences in height, length and width.

Coffee fruit has been harvested by mechanical vibration. From the association of factors such as frequency and amplitude of vibration, sufficient vibrational energy can be transferred to detach the fruits. Thus, from the knowledge of the model properties of the fruit-peduncle system, appropriate frequency and amplitude levels can be employed to perform selective or total fruit harvesting (Santos et al., 2010).

According to Guedes (2011), the improvement of coffee harvesting machines requires prior knowledge of details concerning the mechanical, geometric and dynamics properties of the fruits and the plant. Guedes (2011) states that experimental tests conducted in laboratory with appropriate machines to analyze the behavior of the fruit-peduncle-branch system can assist in the parametrization and design of harvesting machines.

For Roque and Schievelbein (2016), the development of computational technologies in the agricultural area is not new. On the other hand, it is a daily challenge, since every year new technologies are applied in this area aiming at improving the agricultural production process and reducing it operating costs.

Coffee harvesters have been around for over four decades, but there is still a lack of information on their dynamics relationship with coffee.

Seeking to understand the mechanical behavior of the coffee plant through finite element analysis, Carvalho et al. (2016) simulated the coffee tree in a three-dimensional system and compared it with the behavior of a real plant under static load, validating the methodology for studies to prevent structural problems during mechanical coffee harvesting. Tinoco et al. (2014) observed that with the progression of

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fruit maturation, they lose their elastic capacity.

Determining natural frequencies and vibration modes, Coelho et al. (2016) found that these frequencies decrease as the total mass of the system increases, given the greater number of fruits in solidarity with the stalk. Villibor et al. (2016) used image processing techniques, finding natural frequencies of 11.62 and 13.29 Hz for the red and green maturation stages, respectively.

Besides the importance of studying the frequency, amplitude, brake regulation of oscillation cylinders, fruit detachment forces, mechanical, geometric and dynamics properties of fruits, in mechanical coffee harvesting by vibration, further study and knowledge of the dynamics behavior of the mechanical components responsible for vibration transmission to the coffee tree branches and fruits is also required.

In order to know the dynamics behavior of a coffee harvester's vibrating rods in terms of frequency and amplitude of vibration for different settings, Ferreira Júnior et al. (2016a, 2016b) used instrumentation and signal processing techniques to identify and map the tip movement of the rods during operation. The achieved results made it possible to infer on the recommendation of regulation for mechanical harvesting, selective harvesting and less damage to plants.

In coffee growing, especially for the harvesting process, the pursuit of cost reduction, better harvesting performance, greater selectivity and crop preservation is very important, being of interest to both the coffee grower and the harvester manufacturing industries.

Thus, seeking to understand the vibration dynamics of coffee tree branches during harvesting, this work was aimed to determine the vibration behavior of coffee plagiotropic branches, in terms of frequency and amplitude of vibration, in order to raise the displacement profile, that is, the trajectory of these branches in different settings recommended for mechanical coffee harvesting, with the aid of signal processing and instrumentation techniques.

2. Materials and methods

The tests were carried out in the experimental area of Fazenda Bela Vista, in Nepomuceno, Minas Gerais State, Brazil. It was used a self-propelled coffee harvester, model K-3 Challenger, manufactured by the Brazilian company Máquinas Agrícolas Jacto S/A.

The harvester was configured with 13 × 570 mm (diameter × length respectively) shanks on the 22 lower flanges of the oscillating cylinders and 13 × 600 mm shanks on the 14 upper flanges. It is noteworthy that original rods recommended by the harvester manufacturer were used.

Rods positioning configuration was chosen based on the length of the lateral (plagiotropic) branches along the plant (shorter branches at the top and larges at the bottom), as the crop appeared at harvest time.

The plants were instrumented with accelerometers in two positions, upper middle part and lower middle part, as shown in Fig. 1. Note that the upper and lower sensors were fixed at an average height of 1600 mm and 700 mm from the ground, respectively, and approximately 220 mm from the orthotropic branch. The sensors were fixed on the branches by using electrical tape and it was guaranteed during the experiment that there was no detachment of the sensors from the branches. It is important to mention that it was ensured that the accelerometers remained with their axes in the horizontal and vertical planes.

In order to find out the "peak to peak" amplitudes performed by the coffee tree branches at the time of harvesting, the sensors were fixed to the branches, in a position that coincides with the place where the tips of the harvester's rods pass (Fig. 1).

The instrumented branches were plagiotropic branches of primary order, as they had leaves, fruits and branches of higher order also with leaves and fruits.

Due to the complexity and difficulty of practical instrumentation of the plant, the experiment focused on obtaining information from only one side of the plant (facing the inter-row), however, harvesting conditions are similar for both sides.

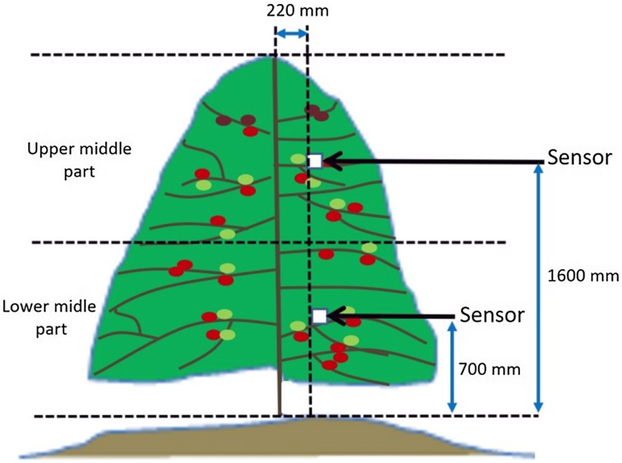

Fig. 1. Sensor mounting position on coffee tree branches.

During the tests the two harvester cylinders remained vibrating in the same setting conditions.

The sensors (accelerometers) were positioned on the plagiotropic branches, one third of their length (from the center of the plant to the end of the branch), as shown in Fig. 2, where in (a) and (b), the sensor is positioned in the branch of the upper part (c) and (d) in the lower branch of the plant.

As the tests were performed under real conditions, dynamically with the harvester passing over the instrumented plants, the sensors were protected to prevent possible mechanical damage.

2.1. Signal acquisition system

The developed system uses a capacitive tri-axial accelerometer sensor, model MMA7361 (Seifert and Camacho, 2007), which has Bandwidth Response of typically 400 Hz and sensitivity of 800 mV/g. This sensor converts the mechanical movement performed by the coffee tree branches into voltage signals that correspond to acceleration. It is a

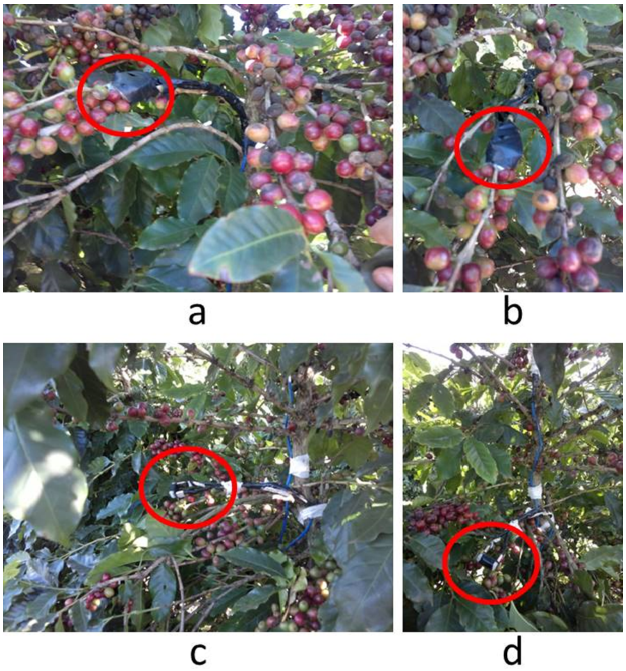

Fig. 2. Position of the sensors in the upper plant branch in (a) and (b) and in the lower plant branch in (c) and (d).

sensor widely used in three-dimensional gaming systems such as motion and tilt sensor, event logger and safety device. It has also been employed to detect mechanical failures of balance beams through vibration signals (Barbosa et al., 2016).

In this study, the accelerometer sensor was used to record the acceleration from the machine and plant interaction. This sensor was chosen mainly due to its low cost, low current consumption (400 mA) and low voltage operating (2.2 a 3.6 V) (Seifert and Camacho, 2007).

To acquire the acceleration signals captured by the sensor, a microcontroller with open source hardware (Arduino model Mega 2560) was used. Besides being attractive because it is “open source”, its use in this work was also due to its low acquisition cost.

The signals were transmitted to the Arduino microcontroller directly via Unshielded Twisted-Pair (UTP) category 5e (certified for data transmission and higher capacity) cables. To storage the collected data, a microcomputer was used.

The Arduino was powered via Universal Serial Bus (USB) directly from the microcomputer.

The machine promotes the excitation in the horizontal direction of the branches. The vertical balance occurs as a consequence and contributes to the detachment of the coffee fruits. The axial movement is also a consequence but, according to the opinion of experts of the coffee area, this movement does not favour the harvest of coffee fruits and can damage the plant. In order to evaluate branch amplitudes in the vertical and horizontal directions of the branch, only two axes were used for acquisition and analysis.

Fig. 3 shows schematically the scheme of the signal acquisition system. The yellow wires represent the connection of the accelerometer X and Y axes. The wires responsible for converting analog to digital signals are represented by dark blue wires. Microcontroller power is represented by the thicker light blue wire connecting the microcontroller to the microcomputer. The accelerometer power is represented by the wire of red color.

2.2. Signal processing

Signal processing constitutes a fundamental step for the final analysis of the collected data, since it is applied in this work with two main goals: reduction of electrical and mechanical noise, and the conversion of the acceleration signal acquired by the accelerometer to position.

The signals obtained by the sensors were collected at a sampling frequency of 6000 samples every 60 s following Nyquist’s theorem (BRANDT, 2011). This implies a sampling time of 30 ms, which leads to a sampling frequency of 100 Hz. This sampling frequency is enough, since the maximum excitation frequency set in the harvester’s displacement was 15.83 Hz (950 cycles.min^{-1}). These signals were stored in spreadsheets and processed via MatLab R2011b®.

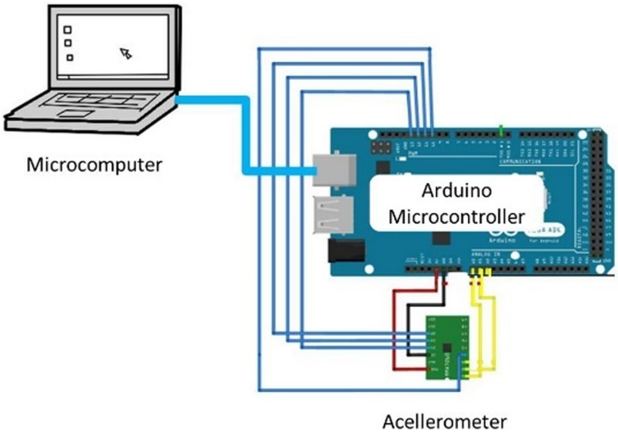

Fig. 3. Acquisition system scheme.

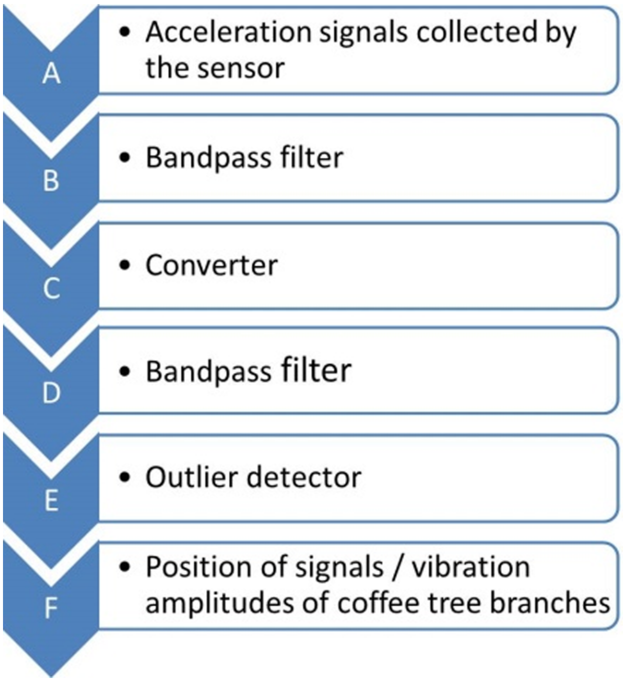

Fig. 4. Steps of signal conditioning.

Next, the acceleration signals were conditioned in order to obtain the signals related to the branch position and then its displacement. For this, basically six steps were performed, as shown in Fig. 4.

After signal collection, the second block implements a pass filter set for each oscillating cylinder tuning frequency (12.5, 14.2 and 15.8 Hz) recommended for mechanical harvesting (SILVA et al., 2015; Ferreira Júnior et al., 2016a, 2016b). The purpose of this filter is to eliminate both electrical and mechanical noises captured by the accelerometer.

According to the note AN3397, developed by the accelerometer sensor manufacturer (Freescale Semiconductor), authored by Seifert and Camacho (2007), a moving average filter for noise reduction is required. Unlike, we applied a bandpass filter that is more restricted to the frequency of interest and attenuates noise at the other frequencies.

Infinite Impulse Response (IIR) filters (6th-order Chebyshev Type II, 40 dB (decibel) attenuation in the reject range and 3 dB ripple in the pass range) (Mitra, 2011) were designed for each cylinder regulating frequency. These types of filters have the property of minimizing the error between the ideal and real filter characteristics with respect to the filter range and lead to lower order filters, which implies less computational complexity. The frequency range of the filters is shown in Table 1.

It should be noted that the filter pass range was defined according to the measured frequency of regulation (from the frequency spectrum analysis of the collected signals), which was slightly lower than the adjusted frequency of the harvester.

The third block (block C) of Fig. 4 refers to the conversion of the acceleration signals to position. Since the sensor picks up the vibration signals in the acceleration form and the objective of this research is to map the displacement profile of the plagiotropic branches of the coffee plant, it is necessary to convert these signals to obtain the position of

Table 1
Filter frequency range.

Regulation Frequency (adjusted on harvester)	Passing range (passing band)
750 cycles. min^{-1} (12.5 Hz)	10.5–14.5 Hz
850 cycles. min^{-1} (14.2 Hz)	12–16 Hz
950 cycles. min^{-1} (15.8 Hz)	14–18 Hz

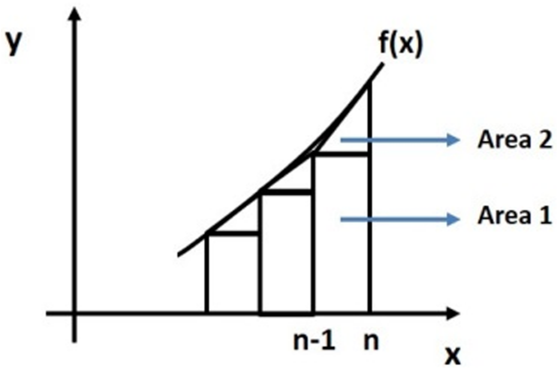

Fig. 5. Computation of the area under the curve $f(x)$.

the branch collected by the sensor. This conversion was based on the note AN3397 (Seifert and Camacho, 2007), which uses the principles of physics and mathematics to convert acceleration into position.

Acceleration is the rate of change of the velocity of an object. At the same time, velocity is the rate of position change of that same object (Seifert and Camacho, 2007). Once the acceleration data is obtained, it is possible, through the double integration of the acceleration signals, to find the position of the signals in time, according to

$$\iint a(t)dt = s(t) + C_1 v(t) + C_2, \tag{1}$$

where $a(t)$ is the acceleration function, t refers to time, $s(t)$ is the position, $v(t)$ is the velocity and C_1 and C_2 are constants. The integral of the acceleration variable results in velocity and the velocity integral in position.

To perform this procedure, the note AN3397 (Seifert and Camacho, 2007) recommends dividing the area under the acceleration curve in the Cartesian plane into rectangles as well as triangles in order to minimize the influence of the sampling error that can be generated during the signal integration process. Fig. 5 exemplifies this procedure, where the area under the curve $f(x)$ is divided into rectangles (Area 1) and triangles (Area 2). The total area under the curve $f(x)$ related to sample n of variable × is computed as

$$area\,[n] = \left(y\,[n-1] + \frac{|y\,[n] - y\,[n-1]|}{2}\right)\cdot \Delta t \tag{2}$$

where $y[n]$ and $y[n-1]$ are the values of variable y (or function $f(x)$) in samples n and n-1, and Δt is the time interval between samples n and $n-1$. The first term of (2) refers to Area 1 and the second one refers to Area 2 of Fig. 5. The procedure described by Eq. (2) was used for both acceleration integration and velocity integration.

The next step, represented in Fig. 4 by Filter C, is used to remove distortions caused by errors in the conversion process of acceleration to position. Non-expected energies were observed to appear at other frequencies in the signal referring to the position $\{s(t)\}$, resulted from the conversion. Thus, a high pass filter could be used to eliminate these distortions, but as the pass band filters (Filter A) were already implemented, they were used here. It is important to mention that the use of these filters remove DC values that are typically present when double-integrating signals in time domain.

The last step depicted in Fig. 4 comprises in eliminating outliers to obtain the most realistic branch displacement values possible. For doing it, the one-class version of the *Support Vector Machine* (SVM) proposed by Scholkopf et al. (2001) was applied. This detector finds a closed hyperplane that divides the data into two classes, so that all points with the same characteristics are inside the hyperplane, and the points considered outliers are outside. It has the advantages of being nonlinear and capable of generating optimal hyperplanes for different data distributions. Besides operating in large spaces, it presents good generalization capacity, since it maximizes the distance between the two classes of the hyperplane (Theodoridis and Koutroumbas, 2008). The method was implemented in MatLab R2011b®.

With the acceleration signals free of interference and outliers, and converted to position, the position signals were plotted on X and Y axes to find the amplitude ("peak to peak") of vibration, i.e. the displacement performed by the coffee branch to which the sensors were attached during the mechanizes harvesting operation.

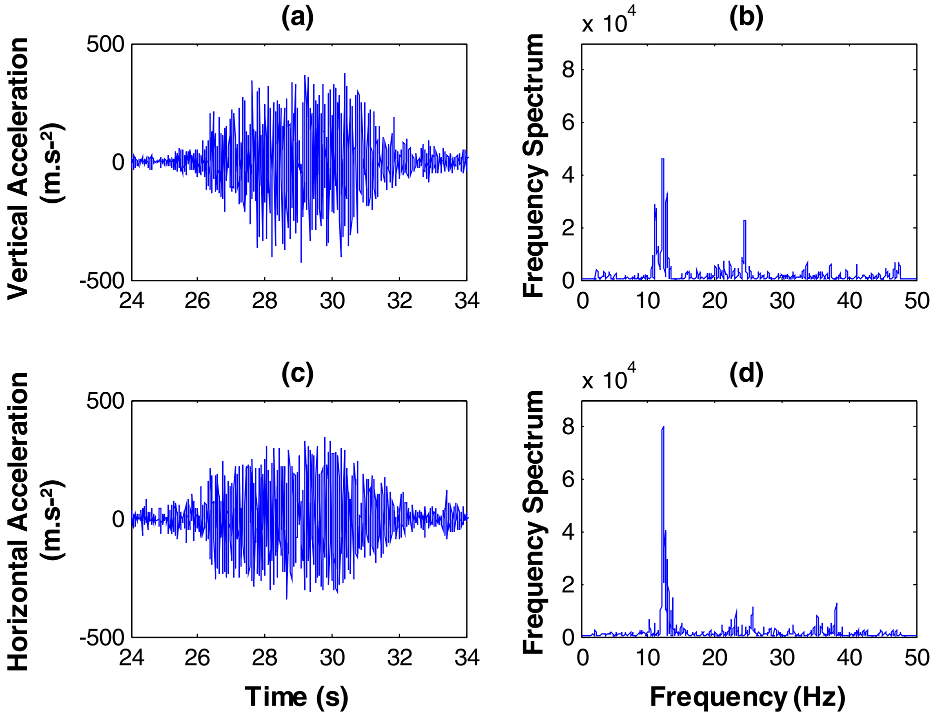

Fig. 6. Acceleration signals collected by the accelerometer sensor and their respective frequency spectra for the 98 N oscillating cylinder brake settings and vibration frequency set at 12.5 Hz. The pairs (a)–(b) and (c)–(d) refer to the vertical and horizontal directions respectively.

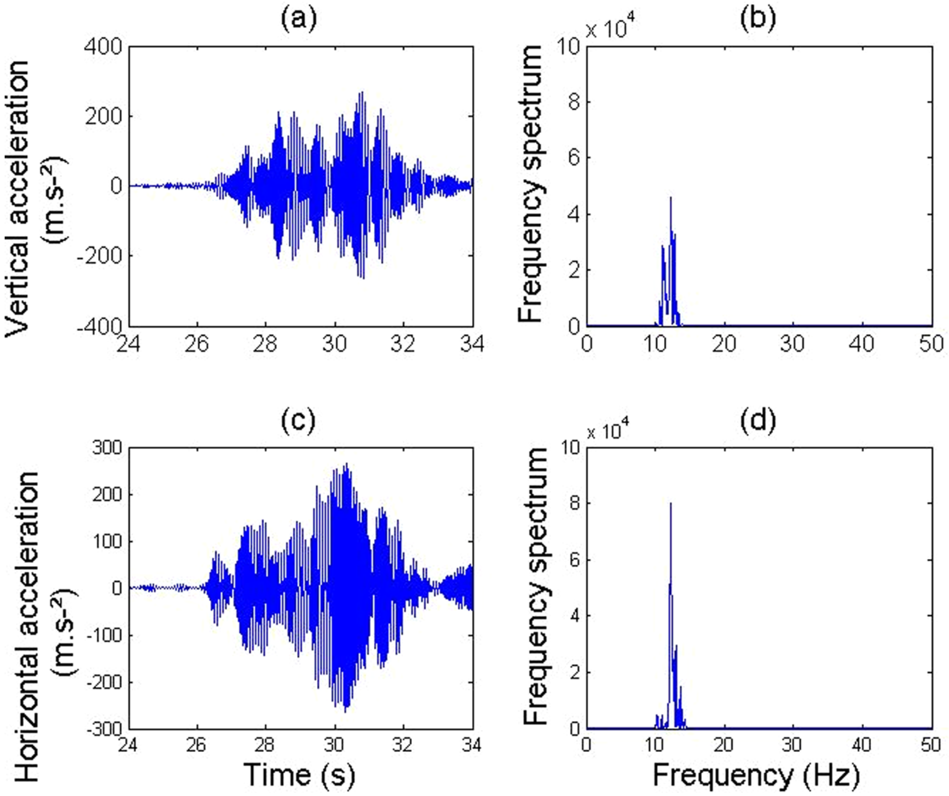

Fig. 7. Acceleration signals filtered by Filter A and their respective frequency spectra for the 98 N oscillating cylinder brake settings and vibration frequency set at 12.5 Hz. Pair (a)–(b) and (c)–(d) refer to the vertical and horizontal directions respectively.

3. Results and discussions

The steps shown in Fig. 4 were applied to all tested settings. For simplicity, the sequential results of each step for only one of the tested settings are presented in this section.

The vibration signals captured by the accelerometer were passed by a high-pass filter (cut-off frequency of 1 Hz) to eliminate non-expected low frequency components (below 1 Hz) with high energy. Fig. 6 shows the vibration signals captured by the accelerometer in the horizontal and vertical directions and their respective power spectrum (pairs (a)–(b) and (c)–(d), respectively) after applying the high-pass filter. These signals refer to 98 N settings on the oscillating cylinder brake, cylinder vibration frequency at 750 cycles·min^{-1} (12.5 Hz), sensor positioned on the plagiotropic branch of the upper middle of the plant and harvester operation at a speed of 950 m·h^{-1}.

The collected vibration signals had a maximum duration of approximately 39 s, however, to improve the visualization of the behavior of these signals over time, the interval was restricted to only 10 s (from 24 to 34 s).

It can be observed, from Fig. 6, that for both directions (vertical and horizontal), there was an energy concentration close to the vibration frequency in which the harvester was adjusted (12.5 Hz). It is observed in (d) higher values of energy at the adjusted vibration frequency when compared to the spectrum shown in (b) that corresponds to the vertical direction. This is because vibration excitation occurs in the horizontal direction.

It is also possible to identify, in Fig. 6, lower energy concentrations in (b) and (d). Between 20 and 30 Hz frequencies of the spectrum shown in (b), there is an energy concentration at the 25 and 26 Hz frequencies. These frequencies are close to the natural frequency values of the fruit-peduncle system found by Ciro (2001) for the first vibration mode, being 26.97 Hz for the ripening stage of green fruits and 25.10 Hz for ripe fruits.

Following the signal conditioning steps represented by the block diagram of Fig. 4, the bandpass filter was applied, and the signals represented by Fig. 7 (vertical and horizontal acceleration and their respective spectra after filtering) were obtained.

With the use of this filter, it can be verified that most electrical and mechanical noise captured by the sensor were filtered, remaining only the signals of the range of interest (energy close to the harvester setting of 12.5 Hz).

The result of converting the acceleration signals into position, performed following the procedure described in Section 2 is illustrated by Fig. 8.

Analyzing the frequency spectrum of the displacement signals obtained, energy concentrations, previously not evidenced at low frequencies (close to 1 Hz) and at frequencies between 20 and 30 Hz, are observed for both directions of vibration (Fig. 8). These small energy concentrations are the result of errors arising from the signal integration during the conversion process, which amplifies the noise. Thus, the bandpass filter was applied again, and a clean signal was obtained, without interference from noise and harmonics (Fig. 9).

Following the steps of Fig. 4, the signals passed through an outlier detector (one-class version of SVM) that creates hyperplanes through support vectors to determine the region that comprise the best behavior of position signals. This region delimits the outliers by creating a separation boundary between them and the rest of the data.

Finally, the position signals that constitute the coffee branch displacement may be viewed in two dimensions (X and Y), representing the vertical versus horizontal displacement (Fig. 10). It results in the estimated trajectory performed by the plagiotropic branches of the coffee tree during the mechanized harvesting operation.

It can be seen from Fig. 10, the branch promoted a maximum vibration displacement of approximately 130 mm horizontally and 110 mm vertically, for the adjustment of 98 N oscillating cylinder brake and vibration frequency set of 12.5 Hz.

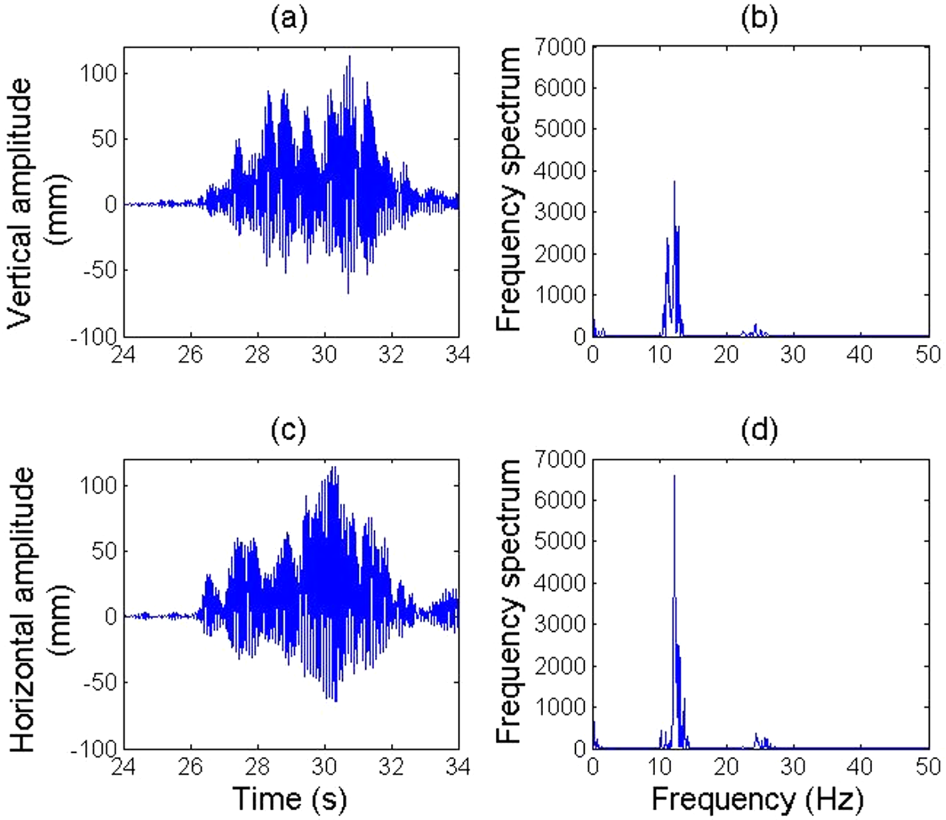

Fig. 8. Signals after conversion process (from acceleration to position) and their respective frequency spectra for 98 N oscillating cylinder brake settings and vibration frequency set at 12.5 Hz. Pairs (a)–(b) and (c)–(d), refer to the vertical and horizontal directions, respectively.

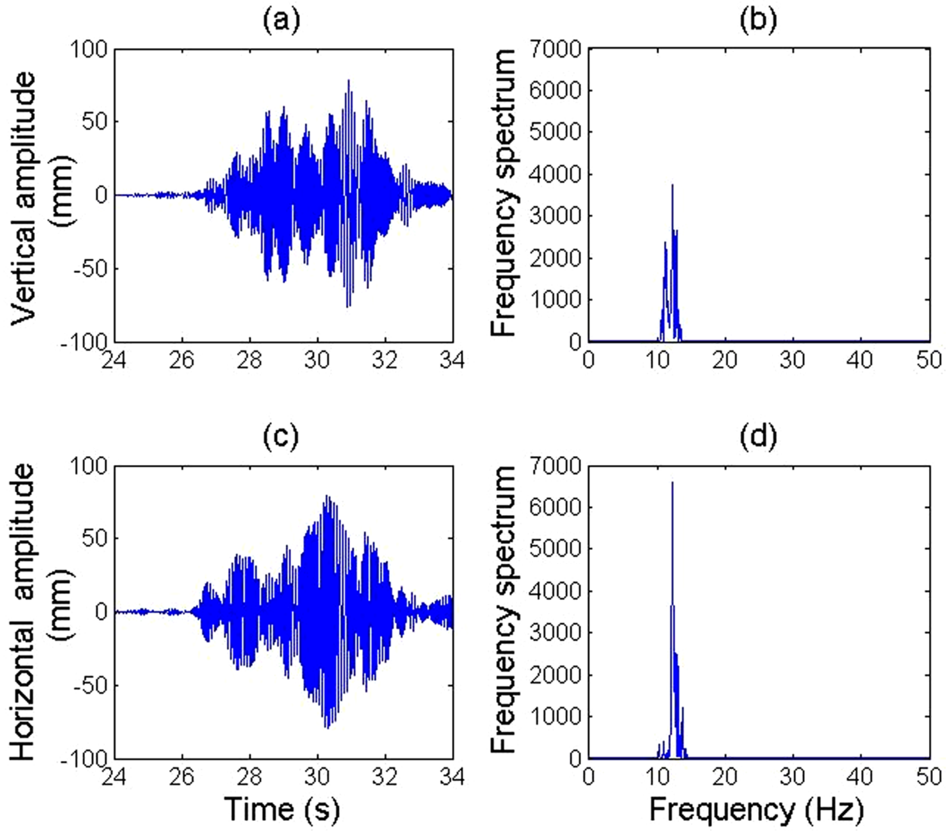

Fig. 9. Filtered position signals and their respective frequency spectra for the 98 N oscillating cylinder brake settings and vibration frequency set at 12.5 Hz. Pairs (a)–(b) and (c)–(d), refer to the vertical and horizontal directions respectively.

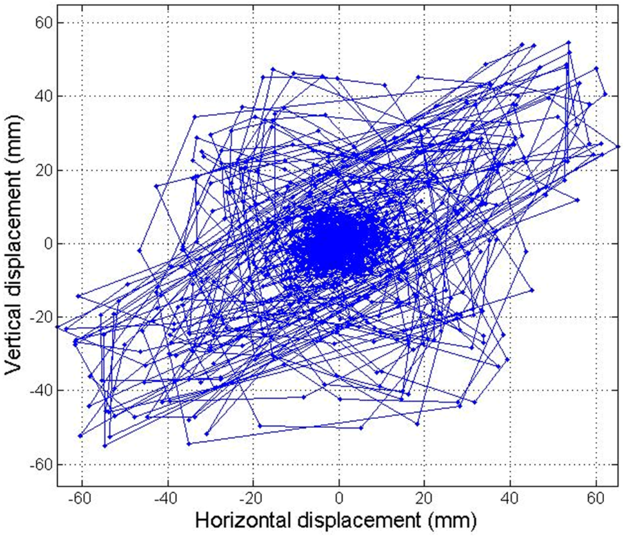

Fig. 10. Displacements made by the plagiotropic branches of the upper middle part of the coffee, referring to the 98 N oscillating cylinder brake settings and vibration frequency set at 12.5 Hz.

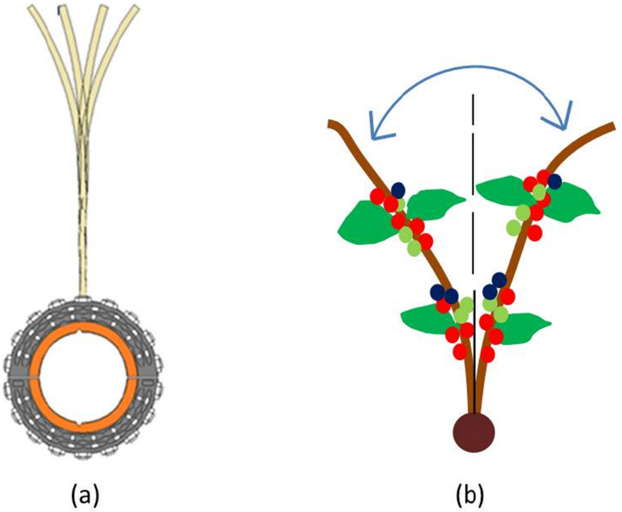

Fig. 11. Overlapping points by the passage of the rods through the central axis and by the passage of coffee branches by the central axis.

It can also be noted that there is a concentration of points (branch movements) in the central part (close to zero of the X and Y axes) of the displacement graph. This is justified by the constant passage of the branch along the central axis, which leads to the concentration of position signals in this region.

Fig. 11 illustrates the situation described about the constant passage through the central axis of both the harvester rods and plagiotropic branches. In (a) the displacements generated by the tip of the harvesting rods are represented and in (b) the displacements resulting from plagiotropic branch vibration found in this work.

Figs. 12–15 show the branch displacement profiles evaluated at other settings for speed harvesting at 950 m·h^{-1}.

For all evaluated adjustments, one can notice a tendency of overlapping of the branch by the central axis exemplified by Fig. 11, consistent with the “back and forth” movement of the coffee branch.

These results show the existence of different behaviors in the branch dislocation trajectory. They also show that the trajectories change according to brake settings, cylinder vibration frequency and between the top and bottom of the plants.

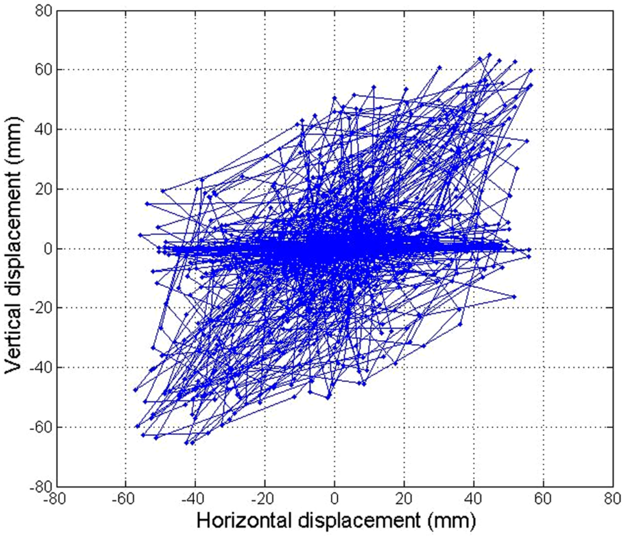

Fig. 12. Trajectory mapping performed by the plagiotropic branch of the upper part of the coffee tree at 78.4 N brake adjustment and oscillating cylinder vibration frequency at 12.5 Hz (750 cycles·min^{-1}).

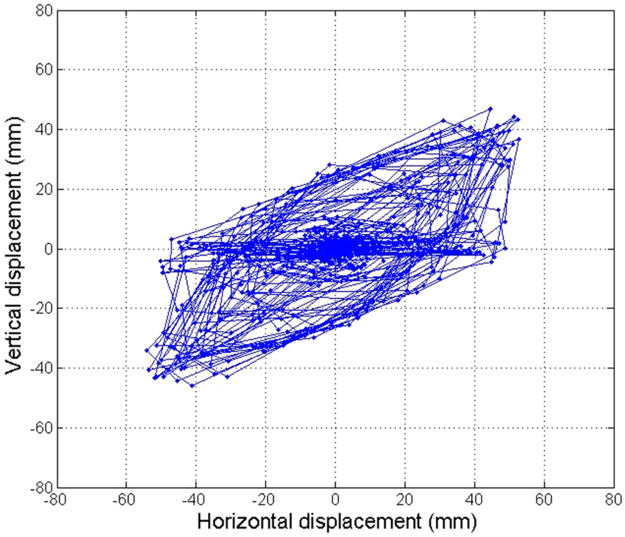

Fig. 13. Trajectory mapping performed by the plagiotropic branch of the lower part of the coffee tree at 98 N brake adjustment and oscillating cylinder vibration frequency at 12.5 Hz (750 cycles·min^{-1}).

Figs. 14 and 15 show coffee branch displacement trajectories with lower vertical and horizontal amplitude for the highest oscillating cylinder excitation vibration (15.8 Hz) and brake adjustment at 78.4 and 98 N, respectively. For these same harvesting adjustments, through practical experimentation, Oliveira et al. (2007a, 2007b) and Silva et al. (2015) found the highest melting efficiency values, therefore the behavior of the coffee branch during interaction with the harvester’s melting rods was still unknown.

So, in an innovative way and through practical experimentation, the present work enables a dynamic understanding of the coffee branch, resulting from the vibration excitation imposed by the harvester.

Through the different amplitudes performed by the branches, obtained in this study, it is possible to infer about the melt systems, and may contribute to the development of new products for mechanical coffee harvesting.

The understanding the dynamics vibration behavior of coffee tree branches can support the production of more specific products that

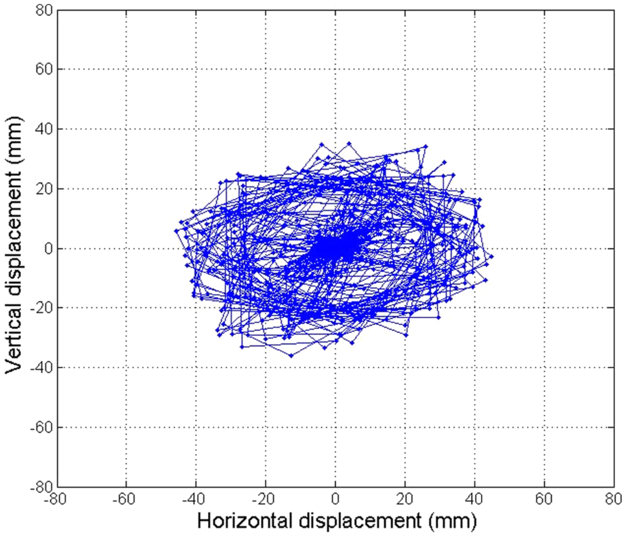

Fig. 14. Trajectory mapping performed by the plagiotropic branch of the lower part of the coffee tree at 78.4 N brake adjustment and oscillating cylinder vibration frequency at 15.8 Hz (950 cycles·min^{-1}).

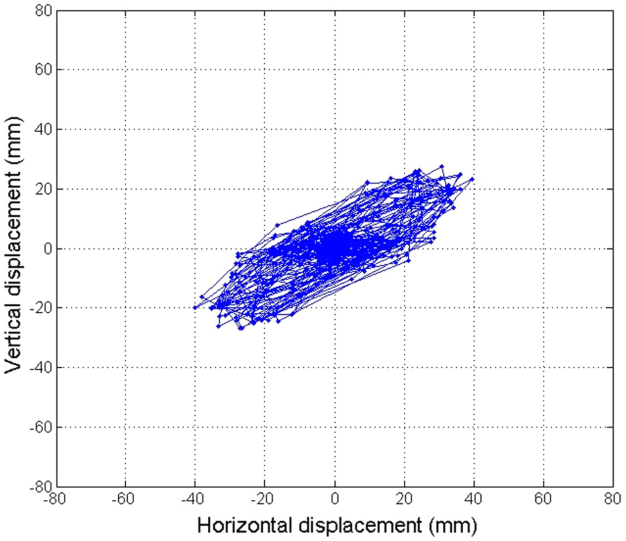

Fig. 15. Trajectory mapping performed by the plagiotropic branch of the lower part of the coffee tree at 98 N brake adjustment and vibration frequency of oscillating cylinder at 15.8 Hz (950 cycles·min^{-1}).

provide better melting efficiency and promote better selectivity of mechanically harvested fruits.

4. Conclusions

The signal acquisition and processing methodology provided agility, clarity and quality in the interpretation of the results, supporting the understanding of the behavior of the coffee tree vibration signals. It is possible to obtain the displacement profile performed by the plagiotropic coffee branches in the different settings tested, obtaining the horizontal and vertical amplitudes (“peak to peak”) performed by them. Note that the instrumentation system proposed takes advantages of being open source and low cost.

The results show the importance of electronics in agriculture, since the study made it possible, through instrumentation and signal processing and conditioning techniques, to estimate the dynamics displacement performed by coffee tree branches at the time of mechanical harvesting. In addition to being innovative, the results effectively contribute to the evolution of products and research, since they allow inferring about the production of new mechanical coffee harvesting systems, which promote greater efficiency of harvesting, greater fruit selectivity and less defoliation of plants.

For future works the authors intend to investigate the axial movement of the branches in relation to the coffee harvesting efficiency and the damaging of the plant.

Author contributions

Luiz de Gonzaga Ferreira Júnior: Collected the data, Contributed data or analysis tools, Performed the analysis, Wrote the paper. **Fábio Moreira da Silva:** Conceived and designed the analysis, Performed the analysis. **Danton Diego Ferreira:** Conceived and designed the analysis, Performed the analysis, Wrote the paper. **Carlos Eduardo Pereira de Souza:** Collected the data, Contributed data or analysis tools. **Andrey Willian Marques Pinto:** Contributed data or analysis tools, Performed the analysis. **Fernando Elias de Melo Borges:** Contributed data or analysis tools, Performed the analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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