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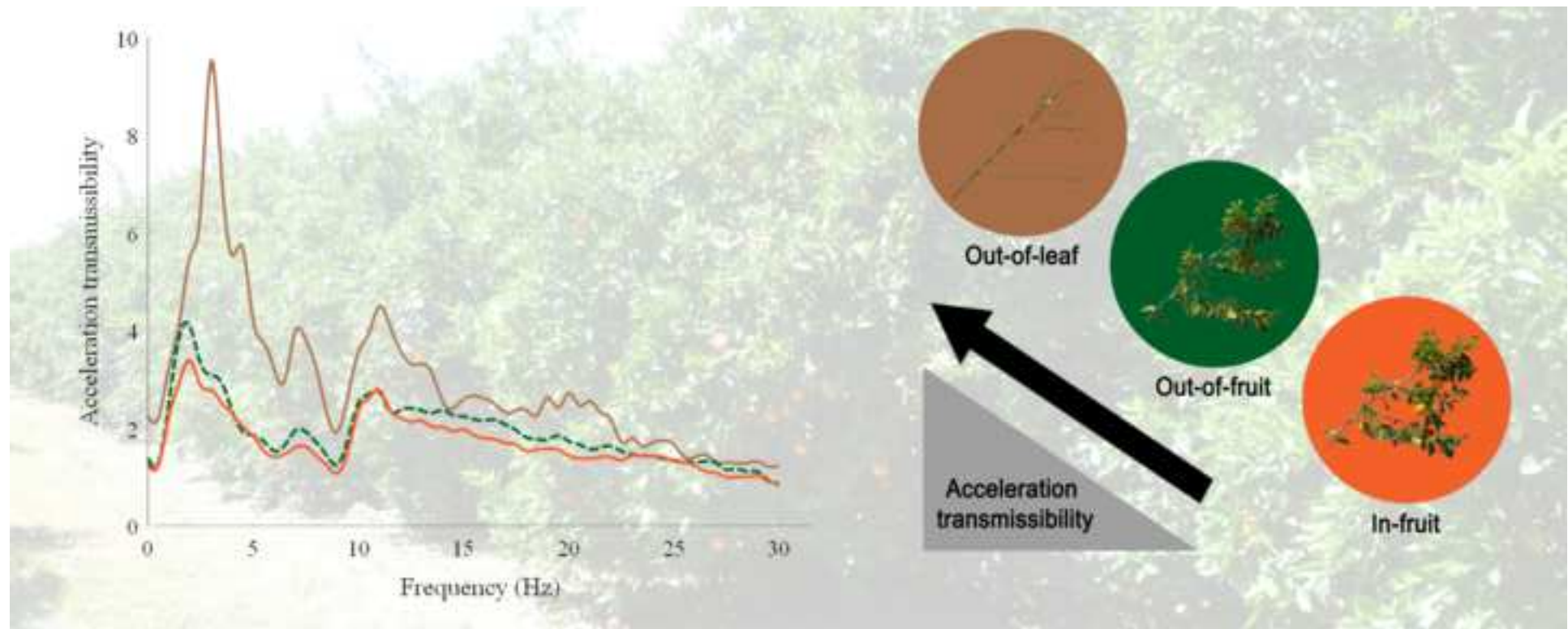
The contribution of fruit and leaves to the dynamic response of secondary branches of orange trees

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Abstract:	The current commercial technologies for mass harvesting fruit are based on the application of forced vibration to the tree, which is transmitted to the fruits causing their detachment. The dynamic behaviour of the plant under forced vibration is of special interest to improve the design and use of the machinery. The objective of this work is to determine the effect of fruit and leaves on the dynamic response of the citrus branch. In this study, 22 secondary branches of 'Valencia' sweet orange trees were tested by applying forced vibration and measuring the response of the branches with triaxial accelerometers. The branches were tested in three stages: in-fruit branch, out-of-fruit branch and out-of-leaf branch. Three natural frequency values were identified in the branches, and were established as 2, 7 and 11 Hz. Acceleration transmissibility along the branch decreased as vibration frequency increased. The acceleration transmission values were highest for the first natural frequency, were up to 1.3-fold in the out-of-fruit branch and up to 4.6-fold in the out-of-leaf branch. The presence of fruits on the branch did not modify the branch natural frequency values but did slightly reduce the values of acceleration transmissibility. However, the presence of leaves on the branches had a double effect, reducing the first natural frequency and drastically damping acceleration transmissibility.
Opposed Reviewers:	
Response to Reviewers:	The response to the editor and reviewers is included in the rebuttal letter

Highlights

- Tested citrus branches showed a similar frequency response to each other
- Three natural frequencies at 2, 7 and 11 Hz were identified in branch response
- Removal of fruit and leaves amplified vibration 1.3 and 4.6-fold, respectively
- Fruit did not modify the natural frequency values of the branch
- Leaves reduced the first natural frequency and drastically damped the vibration

1   **The contribution of fruit and leaves to the dynamic response of secondary branches of**

2   **orange trees**

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19   **Abstract**

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21   of forced vibration to the tree, which is transmitted to the fruits causing their detachment.
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29   11 Hz. Acceleration transmissibility along the branch decreased as vibration frequency
30   increased. The acceleration transmission values were highest for the first natural frequency,
31   and were up to 1.3-fold greater in the out-of-fruit branch and up to 4.6-fold greater in the
32   out-of-leaf branch. The presence of fruits on the branch did not modify the branch natural
33   frequency values but did slightly reduce the values of acceleration transmissibility.
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35   natural frequency and drastically damping acceleration transmissibility.

36   **Keywords:** vibration, mechanical harvesting, acceleration transmission, tree dynamic,
37   damping

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1. Introduction

Nowadays, fruit destined for the fresh market is harvested mainly by hand, while fruit that will undergo industrial transformation may be harvested with mechanised systems. However, in the case of citrus fruits, the harvest for industry remains mainly manual, despite the existence of commercial technology (Roka & Hyman, 2012). The principal obstacles to the introduction of mechanical harvesting are a lack of adaptation of the existing plantations to the machinery, possible damage caused to the trees and low fruit detachment efficiencies (Spann & Danyluk, 2010).

The commercial technologies available for fruit harvesting are based on the application of forced vibration on the branches or trunk of the tree, which is transmitted to the fruits causing their detachment. Among the most widespread mechanised citrus harvesting systems are canopy shakers, with vibration frequency values that are usually lower than 5-6 Hz (Liu, Ehsani, Toudeshki, Zou, & Wang, 2017; Pu, Toudeshki, Ehsani, Yang, & Abdulridha, 2018); trunk shakers, with frequency values ranging from 4.8-8 Hz (Burns, Roka, Li, Pozo, & Buker, 2006) to 14.1-15.5 Hz (Moreno, Torregrosa, Moltó, & Chueca, 2015) and branch shakers, with frequency values up to 18-24 Hz (Torregrosa, Ortí, Martín, Gil, & Ortiz, 2009). The improvement and application of these citrus harvesting systems has been based on a twofold objective: to improve the efficiency of fruit harvesting and to reduce possible damage to both tree and fruit.

The dynamic properties of trees determine their response to external excitation (Spatz, Brochert, & Pfisterer, 2007). Previous works have established the dynamic properties of trees, mainly forest species, with the aim of reducing the risk of tree failure due to wind excitation (Schindler et al., 2010), for safe use in gardening to avoid the fall of trees or branches (Ciftci, Brena, Kane, & Arwade, 2013), for selective mechanical harvesting (Castro-García, Blanco-Roldán, & Gil-Ribes, 2011), for modelling in simulation systems (Jackson et al., 2019) or for fracture analysis (Yang, Yang, & Yang, 2019). However, dynamic studies on tree species of agricultural interest focus on applications in mechanical harvesting. In contrast to forest species, woody species of agronomic interest are oriented to fruit production, with a variation in yield between seasons depending on the species and its management. For citrus fruits, yield can reach (Speck & Spatz, 2004) values from 25,000 to

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45,000 kg ha^{-1} (Burns et al., 2006). In addition, fruit trees may be subject to strong growth restrictions due to training and pruning practices. Tree formation and geometry have direct implications for mechanical harvesting efficiency (Du, Chen, Zhang, Scharf, & Whiting, 2012).

During the mechanical harvesting process, the tree changes from a situation with fruit to a situation without fruit in a short period of time (Zhou, He, Karkee, & Zhang, 2016). This change implies a modification of the tree's mass that could affect its response to vibration and, therefore, the result of the operation. In the case of table olives, Castro-Garcia, Castillo-Ruiz, Jimenez-Jimenez, Gil-Ribes, & Blanco-Roldan (2015) demonstrated that to achieve high harvesting efficiency with trunk shakers, both frequency and acceleration during vibration need to be regulated. Although an increase in the acceleration values applied to the trunk improved harvest efficiency, it also contributed to both fruit and tree damage. In field tests with a trunk shaker in intensive olive orchards, Tombesi, Poni, Palliotti, & Farinelli (2017) showed that the presence of branch suckers during harvesting reduced vibration transmission to the canopy and decreased the efficiency of the operation. Harvesting efficiency, as well as the damage caused to the tree, are conditioned, among other variables, by the frequency of the vibration (Burns et al., 2006). In fact, setting the vibration frequency in the range 4.5-5 Hz can allow canopy shaker systems to discriminate between mature fruit and immature fruitlets (Castro-Garcia, Blanco-Roldán, Ferguson, González-Sánchez, & Gil-Ribes, 2017). The present work is a continuation of these tests with the aim of improving the mechanical harvesting of citrus by vibration.

The dynamic response of trees and their variation during the mechanised harvesting process can contribute to improving the design and use of machines. However, the response of the organs of a plant to dynamic loading can be very complex and sometimes unexpected (Niklas, 1992). One of the methods for determining the influence of various plant organs on plant dynamics is by stepwise removal of plant organs (Speck & Spatz, 2004). The objective of this work is to determine the effect of mature fruits and leaves on the dynamic response of secondary fruiting citrus branches. In this work, an analysis of the dynamic response of the branch is carried out according to the presence of fruits and/or leaves, at a

99   wide range of frequencies that are of interest in the design and operation of mechanised
100   harvesting machinery.

2. Material and methods

102   The tested branches were obtained from two commercial sweet orange orchards (*Citrus*
103   *sinensis* (L.) Osbeck cv. Valencia) located in southern Spain (Cordoba). The first orchard
104   was tested in 2015 and the second in 2019. Both orchards were irrigated, in good
105   phytosanitary condition, had a distance between trees of 7x3 m, and an area of 17.6 and
106   22.3 ha, respectively. Tests were carried out under laboratory conditions during the
107   harvesting season, on a total of 22 branches, i.e. 11 branches per orchard. Three rows of
108   trees were sampled on each orchard and secondary branches with fruits and similar stem
109   diameter were chosen, using simple random sampling and excluding the first and last trees
110   of each row. The branches sampled had ripe fruits, no presence of biotic or abiotic stress,
111   no flowers and, in some cases, small immature fruitlets. During the laboratory test, which
112   lasted 2 to 3 days, the branches were stored in a cold room at a temperature of 5 °C and
113   95% RH, with no changes observed in turgidity and no evidence of wilting.

114   Measurement of the response of the branch to forced vibration was performed in the
115   laboratory, fixing the branch at its base (Figure 1). The branch test was performed as a
116   simple-input and multi-output system. The input was a unidirectional vibration,
117   perpendicular to the branch stem, applied close to its base with an electromagnetic shaker
118   (LDS V406, Nærum, Denmark). A white random noise was used in the frequency range of
119   0 to 60 Hz, with a duration of one minute, in order to avoid possible resonance effects in
120   the branch or the fixation. Vibration amplitude was reduced to avoid detaching fruits or
121   leaves during the test. The response of each branch was considered in multiple outputs,
122   corresponding to the path travelled by the vibration from the point of application to the sub-
123   branch that produces mature fruit. Each branch output was designated as a vibration path.
124   The response of the branch, both at its input and at its multiple outputs, was measured with
125   a set of five piezoelectric triaxial accelerometers (PCB 356A32, Depew, NY, USA) with a
126   measurement range of ±491 m s^{-2}, a sensitivity of 10.2 mV (m s^{-2})$^{-1}$ and a frequency range
127   of 1 to 4000 Hz. Therefore, in the same branch up to four vibration paths could be
128   measured according to the presence and disposition of the fruits.

129   Branches were tested in three stages, as shown in Figure 2. First, the branch was tested with
130   fruits (in-fruit branch), then the fruits were removed (out-of-fruit branch) and finally the
131   leaves were removed (out-of-leaf branch). The accelerometers were placed on the branch at
132   the beginning of the test and remained in the same position throughout all stages of the test.
133   The geometry of the branch and the mass of the different organs were determined during
134   the test. The mass of each vibration path was estimated relative to the total mass of the
135   branch according to its distance from the base, the diameter of the branch and the mass of
136   the fruit.

137   A 16-channel dynamic signal analyser (OROS 36 Mobi-Pack, Meylan, Francia) controlled
138   by signal analysis software (NVGate v.8, Meylan, France) was used to generate the input
139   signal, register, and analyse the acceleration signals. In all, 234 acceleration signals were
140   analysed using a fast Fourier transform analysis, with 401 lines of resolution in a frequency
141   range of 0-60 Hz. The results were averaged to work with a spectral resolution of 0.5 Hz.
142   The response of the branch to vibration was expressed in the three directions of space, so
143   triaxial accelerometers were used for both the input and multiple outputs. For each
144   acceleration sensor, the resultant acceleration was determined as the vector sum of each
145   acceleration signal on the three measuring axes. Subsequently, the ratio between output
146   resultant acceleration and input resultant acceleration corresponding to each frequency
147   value was calculated for each vibration path. This relationship is referred to as acceleration
148   transmissibility (Castro-Garcia et al., 2017). Acceleration transmissibility values above
149   unity indicated an amplification of the vibration applied from the base to the outside of the
150   branch, while acceleration transmissibility values below unity indicated a reduction of the
151   vibration applied.

152   The results obtained from branches and vibration paths, both in physical and geometrical
153   parameters and in response to forced vibration, did not have a Gaussian distribution in all
154   cases. Therefore, non-parametric tests were used in the analysis of the results. However,
155   when normal conditions were satisfied the results were confirmed with parametric tests.
156   The statistical software used for data analysis was IBM SPSS Statistics 25 (International
157   Business Machines Corporation; SPSS Statistics 25, New York, USA).

158   **3. Results**

159　　The acceleration sensor signal data and information on each vibration path of this study are
160　　available at Mendeley Data (http://dx.doi.org/10.17632/j7h954vvzk.2).

161　　The branches tested from the two seasons and orchards were similar in mass, length and
162　　diameter of branch base (Table 1). However, in the first season, the branches had a
163　　significantly lower volume, with fewer fruits and a higher unit mass per fruit than in the
164　　second season (Mann–Whitney U test, $p < 0.05$). In both seasons, the branches had a
165　　proportion of mass of fruits (69.4%), leaves (14.9%) and stem (14.5%) that showed no
166　　significant differences between the seasons (Mann-Whitney U test, $p > 0.05$).

167　　The study of vibration transmission from the branch base to the mature fruit was carried out
168　　with 53 vibration paths: 17 and 36 vibration paths per season respectively. The second
169　　season had a higher number of mature fruits per branch and, therefore, it was possible to
170　　establish a higher number of vibration paths. Although the average mass of the vibration
171　　path in the first season was higher than in the second season (Mann–Whitney U test, $p <$
172　　0.05) , the proportion between fruit mass (76.4%), leaf mass (11.9%) and stem mass
173　　(10.9%) did not present significant differences between season (Mann-Whitney U test, $p >$
174　　0.05).

175　　Figure 3 shows acceleration transmissibility in the vibration paths within the frequency
176　　range of 1 to 30 Hz for the three branch stages studied. The transmissibility of acceleration
177　　varied considerably depending on the vibration frequency applied. However, the response
178　　of each vibration path presented a similar pattern for each branch stage. In the frequency
179　　range between 30 and 60 Hz, acceleration transmissibility showed a decreasing trend, with
180　　similar values for all three branch stages.

181　　The out-of-leaf branch stage achieved the highest values of acceleration transmissibility
182　　compared to the other branch stages. In the out-of-leaf branch stage, three predominant
183　　values of vibration frequency were identified where maximum values of acceleration
184　　transmissibility were produced. These frequency values with maximum acceleration
185　　transmissibility were obtained repeatedly in the in-fruit and out-of-fruit branch stages.
186　　These maximum values were identified as the natural frequencies of the vibration paths,
187　　corresponding to three modes of vibration, where high vibration amplification values were

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188 generated in relation to the vibration applied. From a frequency value of 15 Hz, the
189 differences between acceleration transmissibility in the different branch stages reduced and,
190 from 30 Hz, these values had a similar pattern.

191 Table 2 summarises the frequency and acceleration transmissibility values for each
192 vibration path corresponding to the natural frequencies. The first natural frequency was
193 located at 2.0 Hz for the in-fruit and out-of-fruit branch stages. However, by removing the
194 branch leaf, the first natural frequency value increased significantly to 3 Hz (Kruskal-
195 Wallis test, $p < 0.05$). At the first natural frequency, the vibration was amplified 4-fold
196 from the base of the branch to the peduncle of the fruit. By removing the fruits, the
197 acceleration transmission increased 1.3-fold, whereas by removing the leaves, acceleration
198 transmission increased 4.6-fold, with significant differences between the three branch
199 stages (Mann–Whitney U test, $p < 0.05$). The second natural frequency was displayed at a
200 value of 7.0 Hz, where vibration amplification was 1.9-fold. By eliminating the fruits and
201 then the leaves, the value of the second natural frequency was maintained but the values of
202 acceleration transmissibility for each new branch stage increased. The third natural
203 frequency value was produced at a frequency of 11 Hz, with no significant differences
204 between the acceleration transmissibility values of the in-fruit and out-of-fruit stages. The
205 greatest difference between acceleration transmissibility values for the natural frequency
206 values was obtained by removing the leaves. In the out-of-leaf stage, acceleration
207 transmissibility values decreased significantly (Kruskal-Wallis test, $p < 0.05$) as the natural
208 frequency value increased.

209 For the in-fruit stage at the first natural frequency, the acceleration transmissibility values
210 decreased as the mass of each vibration path increased (Pearson = -0.321, $p < 0.05$, n = 53).
211 This same result was observed in the third natural frequency for the three branch stages
212 (Pearson = -0.292, -0.329 and -0.314, $p < 0.05$, n = 53, respectively). On the other hand, for
213 other values of natural frequencies, the mass of the vibration paths showed no significant
214 linear correlation with the values of acceleration transmissibility.

215 For the out-of-fruit and out-of-leaf branch stages at the first natural frequency, the values of
216 acceleration transmissibility increased as the length of the vibration path increased (Pearson

217 = 0.358 and 0.587, $p < 0.05$, n = 53, respectively). However, this result was not found in the
218 on-fruit branch stage for the natural frequency values.

219 **4. Discussion**

220 The secondary fruit branches maintained a proportion with regard to the distribution of
221 mass in the different organs -fruits, leaves and stem- despite the differences obtained
222 between the values for volume of branch and number of fruits between the two seasons. In
223 order to reach a balance between plant organs, a high number of fruits per tree is associated
224 with small-sized fruits (Blanke & Bower, 1991). Guardiola & García-Luis (2000)
225 demonstrated, for several varieties of orange and mandarin, that there is an inverse
226 relationship between the number of flowers and the size of the fruit, as well as between the
227 unit mass of the fruit and the number of fruits on the tree. For this purpose, the tree
228 establishes a regulation between the foliar part and fruit production. For the 'Valencia'
229 variety, the ratio between leaf area and mature fruit is set at 800 cm^2 of leaf, i.e.
230 approximately 40 leaves per fruit (Rongcai et al., 2005). Confirming this result for woody
231 species, Sun et al. (2019) demonstrated that there is a relationship between biomass and
232 branch diameter that is independent of species or branch height.

233 The branches showed a similar response to vibration in the tested frequency range, but with
234 a different magnitude of acceleration transmissibility depending on the branch stage tested.
235 The proportion of mass between the different branch organs could have contributed
236 decisively to the homogeneity of branch dynamic response, giving the properties of the
237 materials a less prominent role (James, Dahle, Grabosky, Kane, & Detter, 2014). In the
238 frequency range, branches responded with maximum acceleration transmissibility values in
239 frequency values that corresponded to structure vibration modes (Bunce, Volin, Miller,
240 Parent, & Rudnicki, 2019). Other parameters such as slenderness, stem elastic modulus and
241 damping - which were not determined in these tests - could influence the dynamic
242 displacement amplification factor of the branch (Ciftci et al., 2013). As a result, although
243 the natural frequencies identified were similar between branches, the response of each
244 branch in acceleration transmissibility values was not similar. Théckès, Boutillon, & de
245 Langre (2015) established a mechanism in the tree's response to vibration known as
246 damping by branching, which is shown to have a high ability to attenuate the structure's

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247 response in the range of large amplitudes, i.e. close to natural frequencies. This vibration
248 damping system is very robust against variations of geometry and type of damping of the
249 structure. Rodriguez, de Langre, & Moulia (2008) state that the architecture of trees can be
250 based on scaling laws that reduce their dynamic behaviour to their natural frequencies and
251 other biometric parameters. This same behaviour has been demonstrated in forced vibration
252 of whole trees, where the dynamic properties of large and small trees were similar when
253 subject to a scale law (Castro-Garcia, Blanco-Roldan, Gil-Ribes, & Aguera-Vega, 2008).
254 These results indicate that the dynamic response of secondary fruit branches may be similar
255 with regard to the natural frequency of their vibration modes despite differences in size and
256 number of fruits.

257 4.1. The contribution of fruit to dynamic branch response

258 The presence of fruits in branches implied that 69.4% of the mass was distributed in the
259 external part as point load through the union of the peduncle with the branch. The effect of
260 mass on the dynamic response of the branches was described by James, Haritos, & Ades
261 (2006), who indicated the contribution of mass using the term "mass damping", which is a
262 very efficient mechanism to reduce the harmonic movement of the branches against
263 external excitation and contributes to the stability of the structure. Fruit in the branch
264 produced a reduction of branch response in acceleration transmissibility values, especially
265 at low frequency values (2 Hz), compared to the out-of-fruit and out-of-leaf branch stages.
266 Thus, the presence of fruit contributed to an amplification of the vibration applied from the
267 inside to the outside of the branch. The point load of mature fruits could contribute to the
268 vibration paths behaving as individual damped harmonic oscillators coupled to the stem,
269 improving the structural damping of the branch (Spatz & Theckes, 2013). In fact, the
270 presence of fruit limited the effect described by Ciftci et al. (2013), who found that for a
271 tree without fruit, an increase in branch length corresponded to an increase in vibration
272 transmission. Liu et al., (2017) showed a similar result through an experimental study in
273 citrus-bearing branches. These authors determined an average transmission value of 4.7-
274 fold, for an excitation frequency of 2.5 Hz, from the inside of the tree to the outside part of
275 the canopy. In previous tests of vibration transmission on citrus branches, in order to
276 discriminate the response of mature and immature fruitlets, Castro-Garcia et al. (2017)

277   identified natural frequencies values of 2.0 and 7.0 Hz in fruit response. However, mature

278   fruits in a frequency range of 4.5-5 Hz provided a different response to immature fruitlets.

279   The absence of fruits in branches allowed branch dynamic response to be closer to the

280   experiences described for forest species, especially those with decurrent forms (Miesbauer,

281   Gilman, & Giurcanu, 2014). The branches in the out-of-fruit stage presented a balance

282   between the mass of the leaves and the mass of their stem. When the fruits were removed,

283   there was no change in the values of the natural frequencies, although their participation in

284   the mass of the branch was very important. A similar result was shown by Wu & Lin

285   (1990): eliminating the fruits, considered as a concentrated mass at the free end of a

286   cantilever beam, gave a variation of the first natural frequency values that was negligible

287   when the mass ratio (fruit mass/stem mass) ranged from 3 to 9. Moore & Maguire (2004)

288   found that the natural frequency values for coniferous species were proportional to the

289   geometric parameters of the tree, mainly to the diameter at breast height and at tree height.

290   Other parameters, such as the presence of leaves or the temperature above or below

291   freezing point can contribute to changing the natural frequencies of a tree (Bunce et al.,

292   2019). In studies of the structure of branches, Lee & Jim (2018) showed that the order of

293   branches, ratio diameter and length could affect the properties of the frequency domain of

294   oscillatory motion. Experiments with an open-growing tree showed that modifying the

295   natural frequency by removing branches required the removal of more than 80% of the

296   canopy mass (Moore & Maguire, 2005). The removal of fruits led to a significant increase

297   in vibration transmission in the branches, mainly at low frequency values (2 and 7 Hz).

298   4.2. The contribution of leaves to dynamic branch response

299   When the leaves were removed after fruit removal, there was a 50% decrease in the mass of

300   the branch. The absence of leaves increased the value of the first natural frequency while

301   the acceleration transmissibility compared with the out-of-fruit branch stage also increased.

302   Kovacic, Radomirovic, & Zukovic (2018) found similar results with 1.6-fold increase in

303   natural frequency when removing leaves in a potted tree (*Aesculus hippocastanum*), while

304   Reiland, Kane, Modarres-Sadeghi, & Ryan (2015) showed values of 1.2-fold for red oaks

305   (*Quercus rubra* L.). Other studies corroborated these observations of natural frequency

306   reduction in low frequency vibration modes due to the presence of leaves (Baker, 1997; Hu,

Tao, & Guo, 2008). In a further step, Netsvetov & Nikulina (2010) stated that leaves have a dual effect; on the one hand they are able to reduce vibration transmission by working as an aerodynamic damper and on the other as a mass that reduces damping. The effect of leaves is accentuated the more external they are in the canopy. Du, Chen, Zhang, Scharf, & Whiting (2013) showed in a high-density sweet cherry orchard that the foliage and fruit caused a significant damping effect on the transmission of vibratory energy along the vertical fruiting shoots, while showing a constant natural frequency value of 8 to 10 Hz. The contribution of leaves to damping is due to the fact that they play an important role in the dissipative mechanisms of these oscillations (Sellier, Fourcaud, & Lac, 2006; Spatz & Theckes, 2013). Once the leaves and fruits have been eliminated, the vibration transmission in the branch is conditioned by branch geometry (Du et al., 2012; Du, Wu, He & Tong, 2015), by the properties of the wood (Jagels, Equiza, Maguire, & Cirelli, 2018) and by the relationship between the diameter and the length of the branch, which alters the properties of oscillations in the frequency domain (Lee & Jim, 2018).

4.3. Implications for fruit mechanical harvesting systems

Mechanical systems for citrus harvesting aim to detach the fruit by vibration, making the tree to move from an in-fruit stage to an out-of-fruit stage. Based on the results, the frequency regulation of the harvesting machine should not be based on the amount of fruit in the tree or be changed during the vibration time. Nonetheless, the application of different frequency values for different parts of the tree has shown a successful result (Pu, Toudeshki, Ehsani, & Yang, 2018). The regulation of the frequency value will depend on the harvesting technology used, with lower values for canopy shaker, ranging from 2 to 6 Hz (Savary, Ehsani, Schueller, & Rajaraman, 2010), and higher values for trunk shakers, ranging from 5 to 18 Hz (Castro-Garcia et al., 2017). This is because each harvesting technology applies the vibration with different amplitude value in different part of the tree. Attention should be paid to the use of a combination of low frequency with high acceleration values, which leads to a high displacement value and this could result in damage to the bark when working with trunk shakers (Whitney, BenSalem E, & Salyani, 2001). However, the size of the tree, based on its leaf mass, has an important effect on vibration transmission and can reduce harvesting efficiency as tree size increases (Castro-

337 Garcia et al., 2017). In the face of reduced harvesting efficiency values for large trees, it is
338 not appropriate to increase vibration frequency when exceeding 11 Hz. In this case, other
339 solutions should be considered, such as adjusting the size of the tree by pruning, using
340 abscission agents or changing the harvesting technology from trunk shakers to canopy
341 shakers.

5. Conclusion

343 Secondary bearing citrus branches show the same first three natural frequency values under
344 forced vibration conditions. The natural frequencies of the branch are determined by the
345 stem, while acceleration transmission values are conditioned by the presence of fruits and
346 leaves. The presence of fruits does not modify branch frequency response, but does reduce
347 acceleration transmissibility, especially at low frequencies. The leaves provide a twofold
348 effect: on the one hand, a remarkable damping of the vibration and, on the other, a
349 modification of frequency response for low frequencies. The selection of a suitable
350 vibration frequency value for the tree is decisive for mechanical citrus harvesting.

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480

481 **Figure captions**

482   Figure 1. Layout of the dynamic response test of citrus branches with a single input from an

483   electromagnetic shaker and multiple outputs along three vibration paths according to the

484   presence of mature fruit.

485   Figure 2. Citrus branch response to forced vibration, tested in three stages: (a) in-fruit

486   branch, (b) out-of-fruit branch, (c) out-of-leaf branch.

487   Figure 3. Median and interquartile range values of acceleration transmissibility for the

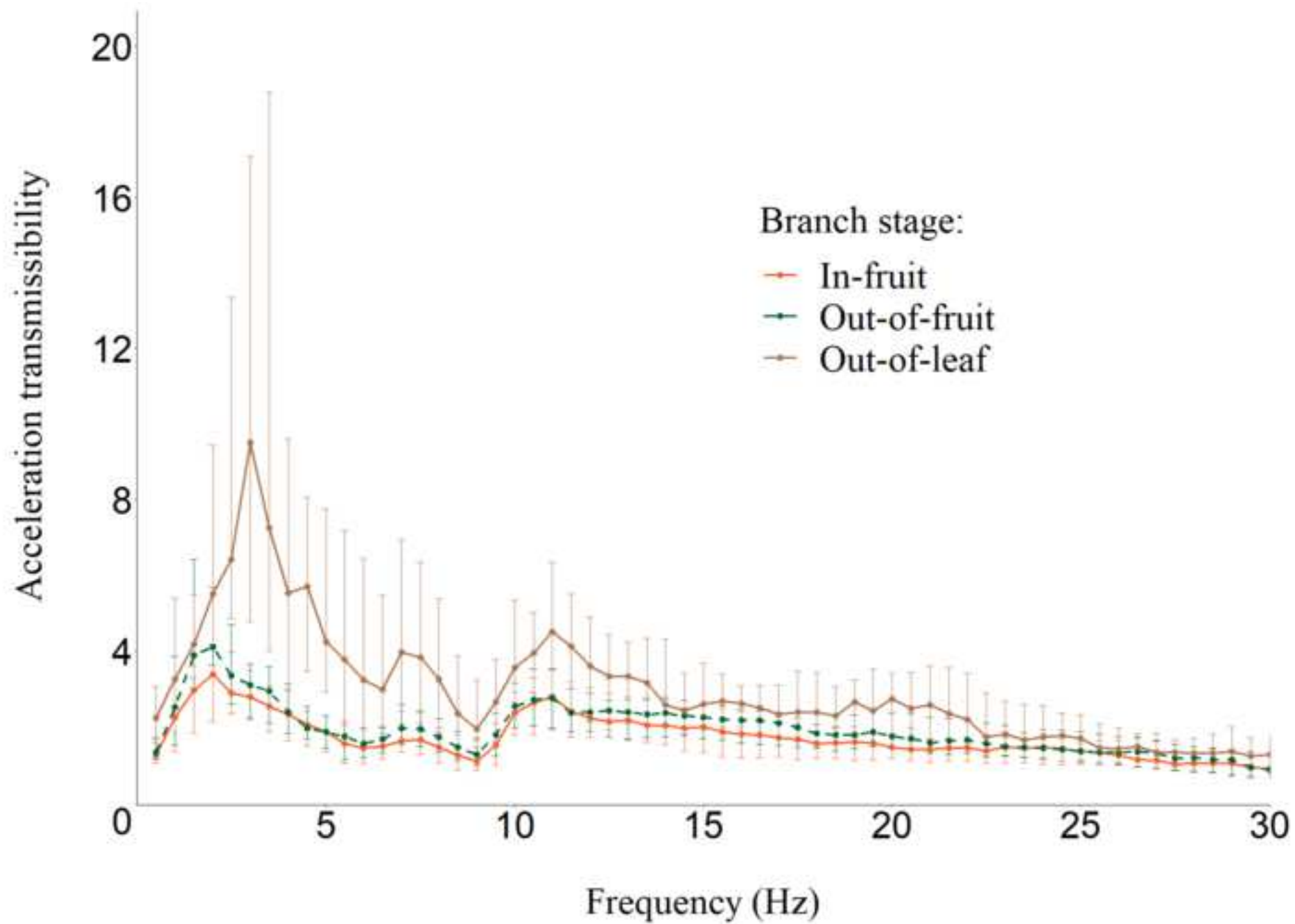488   vibration paths (n = 53) from branch base to fruit stem for each branch stage tested.

Figure 1

Figure 2

(a)   (b)   (c)

Figure 3
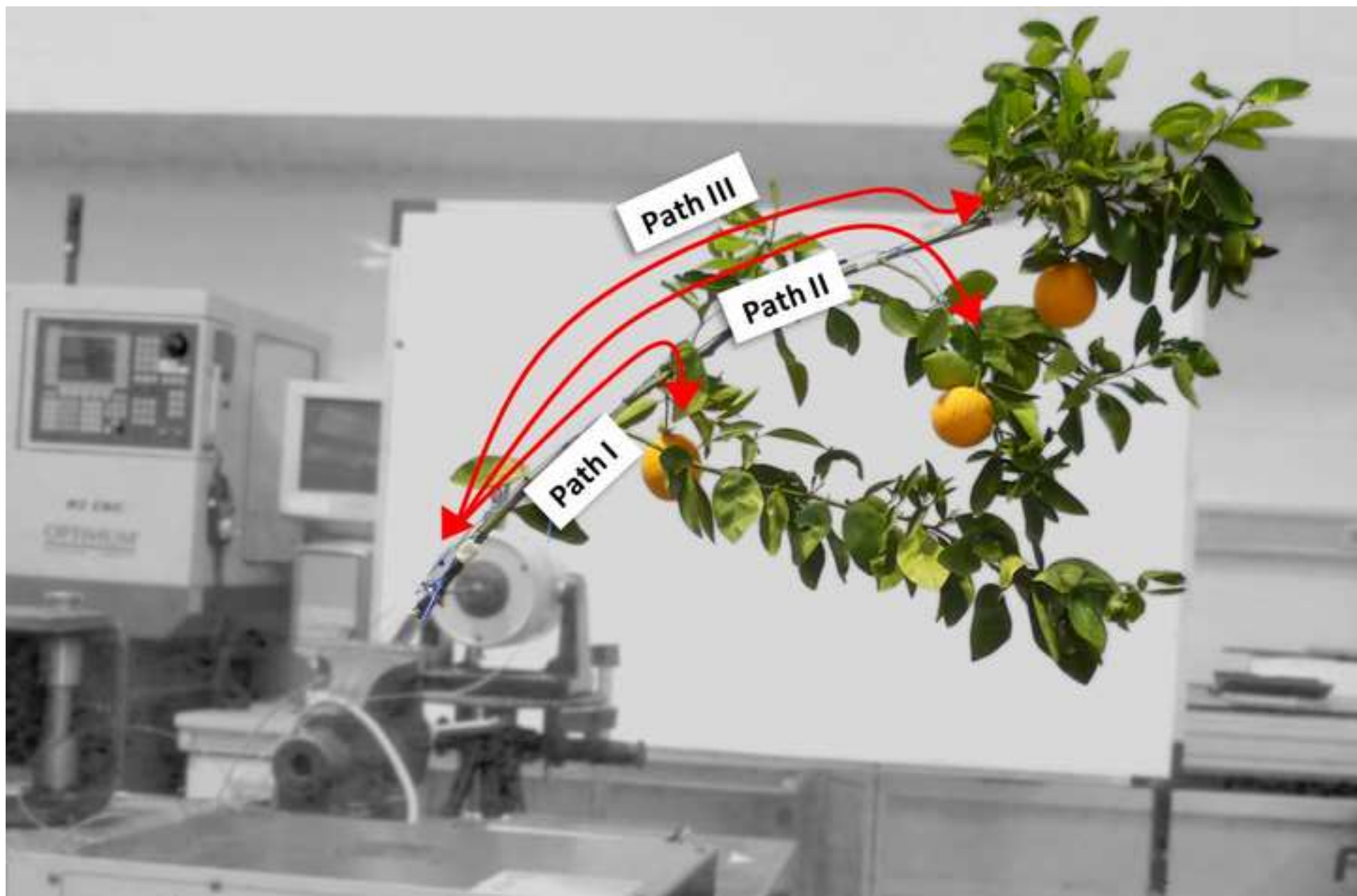
Table 1

Table 1. Characteristics of the tested branches according to the harvesting season.

Harvesting season	2015	2019	All
Number of branches	11	11	22
Mass (g)	1925 (670) a	1817 (555) a	1892 (631)
Length (cm)	120 (30) a	120 (30) a	120 (28)
Volume (L)	91.6 (115.2) a	150.8 (99.6) b	117.5 (119.9)
Diameter of the branch base (mm)	16.7 (5.0) a	16.1 (1.9) a	16.3 (3.0)
Number of mature fruits per branch	4.0 (2.0) a	9.0 (4.0) b	6.0 (5.0)
Unit mass of fruits (g)	252 (62) a	145 (62) b	203 (109)
Fruit mass (%)	69.9 (19.2) a	68.8 (9.4) a	69.4 (11.1)
Leaf mass (%)	14.6 (12.9) a	15.3 (7.7) a	14.9 (8.1)
Stem mass (%)	13.6 (8.4) a	16.0 (4.9) a	14.5 (5.4)

Values shown are median and interquartile range in brackets

A different letter in the same row indicates a significant difference (Mann–Whitney U test, $p < 0.05$).

Table 2

Table 2. Natural frequency (Hz) and acceleration transmissibility values identified in the vibration paths response for each tested branch stage during the 2015 (n=17) and 2019 (n=36) harvesting seasons.

Harvesting season	Branch stage	Frequency (Hz)			Acceleration transmissibility		
		2015	2019	All	2015	2019	All
First natural frequency	In-fruit	2.0 (2.3)	2.0 (1.0)	2.0 (1.3)a	2.8 (2.9)	4.2 (2.5)	4.0 (3.1)a
	Out-of-fruit	2.0 (0.8)	2.0 (1.4)	2.0 (1.0)a	6.4 (5.0)	5.1 (4.7)	5.3 (5.0)b
	Out-of-leaf	4.0 (0.8)	3.0 (1.5)	3.0 (1.0)b	18.3 (19.9)	19.5 (21.5)	18.3 (21.5)c
Second natural frequency	In-fruit	7.0 (1.0)	7.0 (0.0)	7.0 (0.0)a	2.2 (0.9)	1.7 (1.1)	1.9 (1.1)a
	Out-of-fruit	7.0 (0.5)	7.0 (0.0)	7.0 (0.0)a	2.2 (0.7)	1.9 (1.3)	2.2 (1.0)b
	Out-of-leaf	7.5 (0.8)	7.0 (0.0)	7.0 (0.5)a	7.6 (6.6)	5.1 (6.5)	6.5 (5.7)c
Third natural frequency	In-fruit	12.5 (3.0)	10.8 (1.0)	11.0 (2.0)a	2.2 (1.3)	3.1 (2.1)	2.8 (1.8)a
	Out-of-fruit	12.0 (4.0)	10.0 (1.0)	10.5 (1.0)a	2.5 (1.1)	3.2 (1.7)	2.9 (1.6)a
	Out-of-leaf	11.0 (2.0)	11.0 (1.0)	11.0 (1.5)a	4.2 (4.1)	5.8 (5.1)	5.2 (4.4)b

The frequency resolution is 0.5 Hz.

Values showed are median and interquartile range in brackets.

A different letter in the same row indicates a significant difference (Kruskal-Wallis test and Mann–Whitney U test, $p < 0.05$).