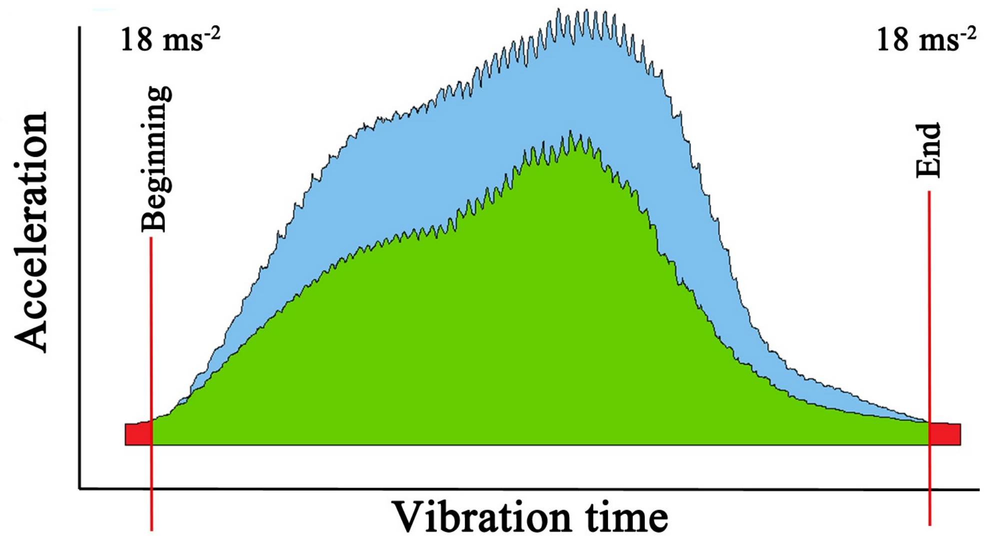
Highlights

- Vibration transmission from harvester to hedgerow is close to 60%
- The main direction of vibration is transverse to the harvester's displacement
- For 62% of the tree vibration time it is in direct contact with the harvester rods
- Acceleration values in the canopy increase with tree height
- There are two canopy zones according to height with different vibration behaviour


1.7g
9.2 g
3.0 g


18 ms-2
18 ms-2
Acceleration
Beginning
End
Vibration time

The vibration behaviour of hedgerow olive trees in response to mechanical harvesting with straddle harvester

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Abstract

Understanding tree behaviour under mechanical harvesting is very important for orchard management and machine design. The objective of this work is to determine the dynamic response of trees, in a hedgerow arrangement, to a straddle harvester with canopy shaker. Forty-four points were measured in random trees at different heights above the ground. The main vibration parameters in the time and frequency domains were analysed. The transmission range of acceleration between machine rods and trees was 58%, vibrating at a similar frequency of 7.8 Hz. The acceleration values registered in the main direction of rod movement were higher than both in the direction of the hedgerow and vertically. The rods of the harvester are in direct contact with the tree canopy 62% of the tree's vibration time. The resultant acceleration values show a temporal distribution similar to a Gaussian curve but distribution throughout the total vibration time shows that only 49.2% of these values are lower than 50 m s^{-2} and 93.3% are lower than 300 m s^{-2}. The analysis of vibration time in a range gives more information about the impact of shaking. The tree responded differently at different canopy heights in terms of acceleration RMS and peaks, identifying two zones.

KEYWORDS: Canopy shaker, super-high density, acceleration, mechanisation, vibration pattern

Introduction

Olive is a crop with strong international importance, and one which is experiencing great development. The traditional plantation layouts of the Mediterranean basin (fewer than 200 trees ha^{-1}) are being changed for ones with smaller tree-spacing such as intensive (200-400 trees ha^{-1}), high-density (400-700 trees ha^{-1}) and super-high-density (over 1500 trees ha^{-1}). These new orchard designs are being adopted all over the world where olive can be grown). The orchard typology choice depends on different factors: ecological conditions, orchard size, manpower availability, economic investment, etc. (Tous, Romero, Hermoso, Msallem, & Larbi, 2014). Each typology has a different tree architecture and so requires different tree training and management.

The design of tree architecture may influence yield and fruit characteristics (Lavee, Haskal, & Avidan, 2012) and is closely related with the harvesting technology to be applied, and thus with crop profitability (Bernardi et al., 2018). The relationship between tree architecture and harvesting technology is, on the one hand, conditioned by the available mechanical harvesting systems, which perform different vibration patterns (Sola-Guirado et al., 2014). On the other hand, tree behaviour under excitation, such as a vibration, is related to the spatial and temporal arrangements of its trunk, branches and shoots. The growth and development of a tree can be controlled by physical parameters such as tree spacing, canopy growth or branching, and by physiological parameters such as leaf density and photosynthetically active radiation (Cherbiy-Hoffmann, Searles, Hall, & Rousseaux, 2012).

The super-high-density olive orchard system is the most suitable for implementing a high degree of mechanisation, which makes it highly attractive for farmers and investors. Its main advantage is fast harvesting, which is performed by straddle harvesters with a canopy shaker, a technology imported from vineyard harvesting. However, years ago, orchards were not adapted to allow continuous harvesting with canopy shakers and were composed of isolated trees suitable for trunk shakers or manual beating. Orchard designs have had to be converted by putting the trees together to create a hedgerow in order to use straddle harvester technology. Tree structure and fruiting must suit the harvesters, but the harvesters must also match the hedgerow features (Connor, Gómez-del-Campo, Rousseaux, & Searles, 2014.; Tombesi & Farinelli, 2017) This work focuses on machine-tree dynamic interaction and their behaviour under mechanical shaking.

Straddle harvesters with a canopy shaker apply a particular vibration by means of the alternate movement of two opposite walls of rods that compress the tree canopy on both sides, while moving forward to the adjacent tree at a uniform ground speed. Several authors have studied canopy shaker regulation on lateral harvesters for other crops such as citrus (Gupta, Ehsani, & Kim, 2016; Pu, Toudeshki, Ehsani, Yang, & Abdulridha, 2018). There are also results for the vibration pattern of canopy shakers on straddle harvesters in other crops such as grapes (Pezzi & Caprara, 2009). The influence of straddle harvesters with canopy shakers in olive orchards has been studied for performance (Ravetti & Robb, 2010), oil quality (Farinelli & Tombesi, 2015), and damage caused to the fruit (Morales-Sillero, Rallo, Jiménez, Casanova, & Suárez, 2014) or the trees (Pérez-Ruiz et al., 2018).

Olive behaviour under vibration in mechanical harvesting has been studied mainly for the application of trunk shakers on isolated trees (Castro-García, Blanco-Roldán, Gil-Ribes, & Agüera-Vega, 2008; Hoshyarmanesh, Dastgerdi, Ghodsi, Khandan, & Zareinia, 2017). In order to gain a deeper understanding of the mechanical harvesting of this modern orchard type, it is necessary to study the two component machine (straddle harvester with canopy shaker) and the tree (olive in hedgerow configuration) (Tombesi & Farinelli, 2014). Optimisation of harvesting will be achieved by maximising fruit detachment, minimising tree damage, and minimising the time spent on the operation. The way to achieve these is to properly adjust the machine parameters and to train trees, which requires an understanding of what happens in the tree structure during harvesting. The objective of this work is to determine the dynamic response of the trees with narrow continuous canopies harvested using a straddle harvester with canopy shaker. The results and the methodology employed may be used in the harvesting of other crops with similar machines and provide suitable advice to enhance mechanical harvesting.

Material and methods

Tests were conducted in an irrigated, super-high-density olive orchard (830 trees ha^{-1}) of the 'Arbequina' cultivar, located in Cordoba (lat: 37° 56' 04.8" N, long: 4° 43' 00.90" W), southern Spain. Trees were over 10 years old, in good physiological and health conditions, with a canopy volume of 5.32 ±1.31 m^3 $tree^{-1}$ and a tree spacing of 2.00 m. Tree pruning had been adapted to over-the-row harvesting systems with a hedgerow diameter of 1.11 m and a canopy height between 0.57 m and 2.95 m from the ground. Harvesting tests were conducted from 14th to 20th December 2017, under similar conditions of weather, fruit ripeness and time of day. These factors play a significant role in the mechanical harvesting efficiency (Camposeo et al., 2013; Farinelli et al., 2012).

The mechanical harvesting system was a straddle harvester (New Holland Braud VX7090, Belgium) with a tunnel 0.60 m wide and with a fixed height of 2.60 m to introduce and compress the tree canopy. The machine had an arrangement of 20 plastic rods on each side with a length of 2.10 m, a vertical spacing of 0.10 m and a horizontal spacing from 0.10 m (rod centre) to 0.60 (rod extremes). The machine ground speed was 0.55 m s^{-1}. Forced vibration was applied by alternate rod movements with a configuration of the harvester set to 460 cycles min^{-1}, as the most suitable for harvesting efficiency and low tree damage, according to the machine operator experience.

Vibration was measured in the trees and machine during harvesting using a set of triaxial MEMS accelerometers (Gulf Coast Data Concepts LLC X200-4, Waveland, MS) with a measurement range of ±2000 m s^{-2}, 16-bit resolution, a sensitivity of 0.06 m s^{-2} and a sampling frequency of 400 Hz. Each sensor in the tree was located behind the branch, to avoid direct contact with rods, coinciding with the vertical direction (Z axis). The transverse axes of the sensor defined a plane parallel to the ground (X and Y axes). The Y axis coincided with the main movement of the rods. There were 44 recorded points distributed randomly in the trees at different heights from 0.65 to 2.40 m from the ground, and the accelerometers were located in the main branches with the same axis orientation. Acceleration sensors in the machine were located behind the rod to avoid direct contact with branches (Figure 1).

Analysis of the acceleration signals was performed in the time domain using R open software (R Core Team, 2016) and in the frequency domain using NVGate v8.0 software, with a Fast Fourier Transformation with 401 lines in a frequency range of 0-156.2 Hz with a 0.39 Hz resolution.

We propose a methodology of analysis to obtain several important variables from the acceleration signals measured on the trees and machine.

In the frequency domain, the vibration variables were:

- Frequency: number of cycles per second (Hz) of rod movement shaking the canopy.

- RMS acceleration (A_{RMS}): root mean square (RMS) of acceleration for each accelerometer axis (a_x, a_y, a_z) for the frequency of vibration (Rao, 2004).

In the time domain, the variables studied (Figure 2) were:

- Resultant acceleration (A_r) (m s^{-2}): vector sum of the three measurement axes (a_x, a_y, a_z) on each sensor.
- Vibration time (T_{vib}): time elapsed between the first and the last event with a value over a resultant acceleration range. This range was obtained by measuring the acceleration at which trees vibrated without any excitation except the action of natural phenomena, in the 150 s before and after harvesting.
- Vibration time in a resultant acceleration range (T_{Ar}): sum of the time intervals above a resultant acceleration range.
- Peak acceleration (A_p): the 21 maximum values of peaks in resultant acceleration in the time domain. The number 21 is a criterion taken assuming a mean frequency of 7 cycles per second and a vibration time of 3 s.

A cluster analysis was carried out with the different sampling points using A_{RMS} and A_p applying the methods of hierarchical clustering, k-means and k-medoids. Euclidean distance was used in all methods. For the hierarchical clustering, the Ward link criterion was used. For k-means and k-medoids, a k-value (number of clusters) of 2 was used, estimated by the elbow method, and the average silhouette method.

Results and discussion

The lowest canopy branches were shaken because of the configuration of the machine height, but also the top branches that were shaken into the tunnel because of their elasticity. The branches vibrated with a frequency of 7.8 ± 0.1 Hz (mean ± sd), very close to the harvester rod shaking frequency, and concurring with the values reported by other authors for similar machines (Pezzi & Caprara, 2009). The frequency at which the trees are excited to detach fruit varies according the harvesting technology used. The vibration pattern is different if excitation is applied to the foliage or directly on the tree structure. A wide ranges of frequencies may be applied for detaching olives directly related with the amplitude of the vibration, but, generally, the technology of the straddle harvester worked on values quite similar to those of the massive lateral canopy shaker and slightly higher than for the hand-held shaker comb but lower than trunk shakers or branch shakers (Sola-Guirado et al., 2014). However, frequency values may also vary for the same machine, as has been reported for the straddle harvester for coffee (12-15 Hz) (Cassia, Silva, Chioderolli, Noronha, & Santos, 2013) or be similar to those in a vineyard (7-8 Hz) (Vallone, Alleri, Bono, & Catania, 2017).

The A_{RMS} values measured on the harvester rods were 174 ± 28 m s^{-2}, while the values measured on the trees were 101± 31 m s^{-2}. This indicates a transmission acceleration rate of 58.2%. This low rate is not as important as in other machines like trunk shakers, where low rates may produce bark damage to the trunk or poor detachment efficiencies (Tombesi, Poni, Palliotti, & Farinelli, 2017). Nonetheless, the transmission rate could be enhanced with better contact between rods and branches as long as there is a proper angle between them (Gupta, Ehsani, & Kim, 2016b), which can only be achieved with branching or modification of the rod tilt. The material of the rods is also important as it may influence not only removal efficiencies but also branch damage (Liu, Ehsani, Toudeshki, Zou, & Wang, 2017; Pu et al., 2018) and durability of the rods themselves.

Several authors have studied acceleration transmission throughout the whole tree structure (Sola-Guirado et al., 2018; Tombesi et al., 2017), but such analysis makes no sense for a straddle shaker because the rods hit many points of the tree structure all over the height that is inside the tunnel, so there is no purpose to analyse the transmission between different points of the tree. Despite this, the tree may be represented as a structure formed by a trunk and branches that are dynamic masses with a damping factor and a spring (James, Haritos, & Ades, 2006). Branching growth angle and contact between the branches in the same row influence the tree's response to the vibration. Tombesi and Farinelli (2014) suggest the adaptation of the canopy to overhead harvesting by removing less potentially-fruiting shoots (i.e., 1-year old shoots) and removing more wood than topping.

Under the described measurement procedure and placing the accelerometers as shown in Figure 1, the breakdown of A_{RMS} on the different axes (x, y, z) showed different values during the shaking process. The main direction of vibration in the tree with values of 92 ± 30 m s^{-2} was the one perpendicular to the hedgerow (axis y), which corresponded to the maximum rod amplitude of the shaking movement. The values registered on the tree in the same direction as the hedgerow and ground speed (axis x) were three time lower than in the main direction of vibration (31 ± 19 m s^{-2}). On the other hand, there were other meaningful components of vibration along the direction in which tree grew (axis z) (17 ± 12 m s^{-2}), despite the fact that the rods only work on a horizontal plane, but which may be due to the slight inclination of trees.

It is quite difficult to calculate the beginning and end of the vibration generated by continuous harvesting systems. In a straddle harvester, this time could be calculated by setting a proper range or minimum resultant acceleration value, which would only occur in the tree due to the interaction of the rods shaking the tree and would finish when that contact ended. For this reason, in this work we recorded the acceleration values generated in trees exclusively by environmental phenomena, mainly wind and gravity, without machine interaction. The mean acceleration was 11 ± 1 m s^{-2} with maximum values of 17 m s^{-2}, so we proposed setting an acceleration range from 18 m s^{-2}. With this range the vibration time was 6.84 ± 1.08 s.

The higher the acceleration range, the lower the vibration time, which reached values from 6.13 s for a range of 30 m s^{-2}, 4.68 s for 100 m s^{-2}, 3.32 for 300 m s^{-2} or 1.21 for 1000 m s^{-2}. Figure 3 shows the mean resultant acceleration values registered in trees over time, starting at the same point with the cited criterion of an acceleration range from 18 m s^{-2}. The A_r values increased until reaching a peak, possibly at the mid-point of the tunnel where the maximum amplitude of movement occurs, and decreased to reach a trough, with a temporal evolution which fits with a Gaussian curve (R^2=0.93). The zone of increasing A_r showed a longer linear evolution than the decreasing zone (Figure 3). This shows how trees have a higher damping of vibration at the beginning of the shake than at the end, despite the high damping of the olive tree (Castro-García et al., 2008). This may be due to the catapult effect that the machine generates when it releases the tree. Figure 3 also shows the average frequency spectrum for the measured points. The frequency analysis showed a main value (7.8 Hz) corresponding to the frequency vibration of the rods and a first harmonic value in double frequency (15.6 Hz) corresponding to the response of the tree and the possibility of double impacts when the rods on both sides of the machine do not hit the tree at the same time.

The vibration time calculated (6.84 s) is considerably longer than the theoretical duration when the rods are beating foliage (4.19 s), which was calculated by dividing the distance covered (the sum of rod length and mean tree diameter) by the machine speed. That is, trees are under forced vibration for a longer time because there is a period of time in which the machine covers and releases the tree. While shaking, there is vibration transmission between trees in the same hedgerow and after shaking there is a time in which the tree remains vibrating freely.

The distribution of the resultant acceleration throughout the vibration time measured in the trees (Figure 4) shows the vibration pattern that the straddle harvester performs is quite similar to that of canopy or foliage shakers (Sola-Guirado et al., 2014). This histogram illustrates that most of the time the resultant acceleration values are low (49.2 % for A_r <50 m s^{-2} and 21.3% for 50 < A_r <100 m s^{-2}) despite there being some resultant acceleration values that are ten times greater but which represent a shorter time. The high values, over 600 m s^{-2}, are only 2.2 % of the vibration time. These values highlight how impacts are not considered in the frequency domain analysis with A_{RMS}. In other harvesting systems, the vibration parameters in the frequency domain are applied as predictors of harvest efficiency and damage (Leone et al., 2015; Hong, Rosa, & Upadhyaya, 2012; Polat et al., 2007; Sessiz & Özcan, 2006). However, in harvesting with lateral or straddle canopy shakers, impacts have a high influence on the efficiency process (Sola-Guirado et al., 2016), so resultant acceleration is not enough for the analysis of the harvesting with this technology and it should be complemented with the impacts values.

Impacts on the branches are generated by high amplitude rod movements while moving forward. The shocks (A_p) had values of 974 ± 375 m s^{-2} (the average of the 21 highest acceleration values, with rebounds removed) with acceleration peaks up to 1607 m s^{-2}. However, despite the high values, the impacts had a fast damping and thus a low duration (Figure 4). The amount of damping determines the energy transferred to the fruit of the tree and may be more dependent on the air drag on leaves and twigs than on the material properties of the wood (Gupta et al., 2016). The tree may act as a damped harmonic oscillator with predominantly mass damping (Castro-García et al., 2008).

For a more in-depth analysis of the intensity of the impacts, the "vibration time in a range" parameter may be calculated. This shows how much time the branches vibrate over an acceleration range that may influence detachment or even damage (Pezzi & Caprara, 2009). In this work, the branches vibrated for a time of 4.43 s, 0.44 s or 0.04 s over ranges of 30, 300 and 1000 m s^{-2}, respectively. The values of vibration time in a range decrease as the bottom acceleration in the range increases, almost reaching an exponential function (R^2=0.93). Nonetheless, this analysis should be taken with caution for several reasons: the resolution or the sampling frequency in the analysis may average the maximum values of the impacts; one single impact is distributed differently along the three axes; and finally, the resultant acceleration value shows the root mean square values and also introduces extra values of peaks that are the result of the rebounds of the impacts on each axis. To increase the vibration time in a range, it would be advisable to reduce the ground speed, prejudicing the machine's work capacity, or to lengthen rods to enhance work performance (Caprara & Pezzi, 2011).

Tree behaviour was different depending on the height at which the vibration occurred and on branch diameter. There was a significant positive linear relation between the average of the maximum 21 peaks of acceleration (A_p) and the height in the tree at which they occur (Pearson = 0.806, p <0.01, R^2=0.65), but also with the average of A_{RMS} (Pearson = 0.794, p <0.01, R^2=0.63) (Figure 5). In contrast, there is a negative significant linear relation of these variables with the diameter of the branch (Pearson = -0.630, p <0.01, R^2=0.40; Pearson = -0.661, p <0.01, R^2=0.44, respectively) (Figure 6).

The cluster analysis with A_{RMS} and A_p obtained a classification in two groups (group 1, N=20 and group 2, N=24) (Table 1) with similarities of 93% between the hierarchical clustering, k-means and k-medoids models. The k-medoids model was selected as it is more robust and less sensitive to outliers. Significant differences (t Student, $p < 0.05$) were found between the groups regarding height in the tree, A_{RMS} and A_P. It seems to indicate that these kinds of trees planted in a hedgerow respond in a different way for the two zones of above and below about 1.50 - 1.70 m. Other authors have found three different behaviour zones in the canopies of big olive trees shaken with canopy shakers (Sola-Guirado, Ceular-Ortiz, & Gil-Ribes, 2017).

The mean coefficient of variation of the RMS and peak acceleration values were higher in the low canopy zone (CV=30.2%, N=24) than in the top canopy zone (CV=16.4%, N=20). This indicates that there is more homogeneity in the top zone due to the compression of this canopy section within the straddle harvester tunnel. However, low tree zones have greater variability, probably because of the great damping effect of the soil that is closer to lower zones (Horvath & Sitkei, 2005), the differences of branching growth along the tree height, but also the damping caused by the interaction of the lowest branches with catching parts. So, canopy features influence tree response to vibration, and may affect mechanical harvesting, but in a different way to tree harvesting with trunk shakers (Tombesi et al., 2017).

Straddle canopy shaker systems are more efficient in trees with a flat, continuous canopy wall (Ferguson & Garcia, 2014) because the shaking tunnel has been designed to perform a similar vibration all over the tree height despite the tree's different response. The results suggest creating different vibration zones in the machine or adjusting vibration at different heights to reduce the level of energy applied to the tree and thus reduce the damage to both tree and fruit (Pérez-Ruiz et al., 2018). Another action would be to adapt tree training in order to distribute fruit production in zones which receive higher acceleration values, considering that the top zone has a higher yield (Trentacoste et al., 2018), higher canopy elasticity (Tombesi & Farinelli, 2014) and training affects yield but not machine harvest efficiency (Raspberry, Strik, & Cahn, 1999). In this study, no significant differences were found between values of tree canopy volume in the mean values for resultant acceleration or peak acceleration.

There were no significant differences between the described zones for vibration time (t Student, $p > 0.05$). However, there were significant differences between both zones for the vibration time in a range, (Figure 7 with intervals of 50 m s^{-2}) for all the intervals except 50-100 m s^{-2} (t Student, $p > 0.05$). This highlights the importance of calculating parameter vibration time in a defined acceleration range as part of an analysis of tree response to any harvesting technology.

Conclusions

The data reported provide a valuable quantitative study of the vibratory phenomena that occur during the mechanical harvesting of olive trees in a hedgerow arrangement with a straddle harvester.

There is a low transmission rate of acceleration between rods and branches that may suggest performing an analysis of the phenomenon as a non-forced or discontinuous vibration. The acceleration range above 18 m s^{-2} may be a good criterion to calculate the vibration time in which tree vibrates due to machine interaction. The energy applied to the tree increases with a Gaussian time distribution, with the highest values of acceleration in the zone of maximum rod amplitude. However, the fruit is mainly detached inside the tunnel with a vibration time of 62% of the total vibration time, so reduced values of fruit detachment force may cause detachment before the action of the harvester.

The acceleration pattern of the straddle canopy shaker shows low values of acceleration throughout time and this conceals the value of impacts that occur in the tree. The analysis of vibration time within a range of accelerations gives an idea of how great and short these acceleration peaks are. These values are very important when studying the fitness of different olive varieties for mechanical harvesting with a focus on developments to aavoid fruit and branch damage.

Three-dimensional tree response was different depending on the direction of rod movements and ground speed direction. The values of resultant acceleration and peaks were also higher in higher parts of the tree. The design of the machine should be adapted in accordance with the different responses of the tree in order to reduce the energy levels in fruit. Likewise, tree training should avoid the concentration of fruits in lower areas, promote external fruiting of the canopy and reduce fruiting in the trunk line.

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Figure Captions

Figure 1. Location of accelerometers in tree and on straddle harvester (Z: vertical tree growth direction, X: machine forward direction, Y: rod movement direction).

Fig.2 Time domain acceleration signal (left) and vibration parameters analysed in each tested tree for an example with an acceleration range of 500 m s^{-2} (right).

Figure 3. Acceleration measured in olive trees performed with the straddle harvester. Left: Time domain analysis of resultant acceleration values for an average of 44 values of 0.0025 s resolution. Right: Average spectrum of canopy vibration with 0.39 Hz resolution.

Figure 4. Histogram of the resultant acceleration measured in trees throughout the vibration time in the time domain (N=44).

Figure 5. Linear relations between acceleration values in tree canopy, root mean square (A_{RMS}) values and peak values (A_p), and tree height during the mechanical harvesting process.

Figure 6. Linear relations between acceleration values in tree canopy, root mean square (A_{RMS}) values and peak values (A_p), and the branch diameter during the mechanical harvesting process.

Figure 7. Distribution of vibration time within different acceleration ranges measured throughout the vibration period (N=44)

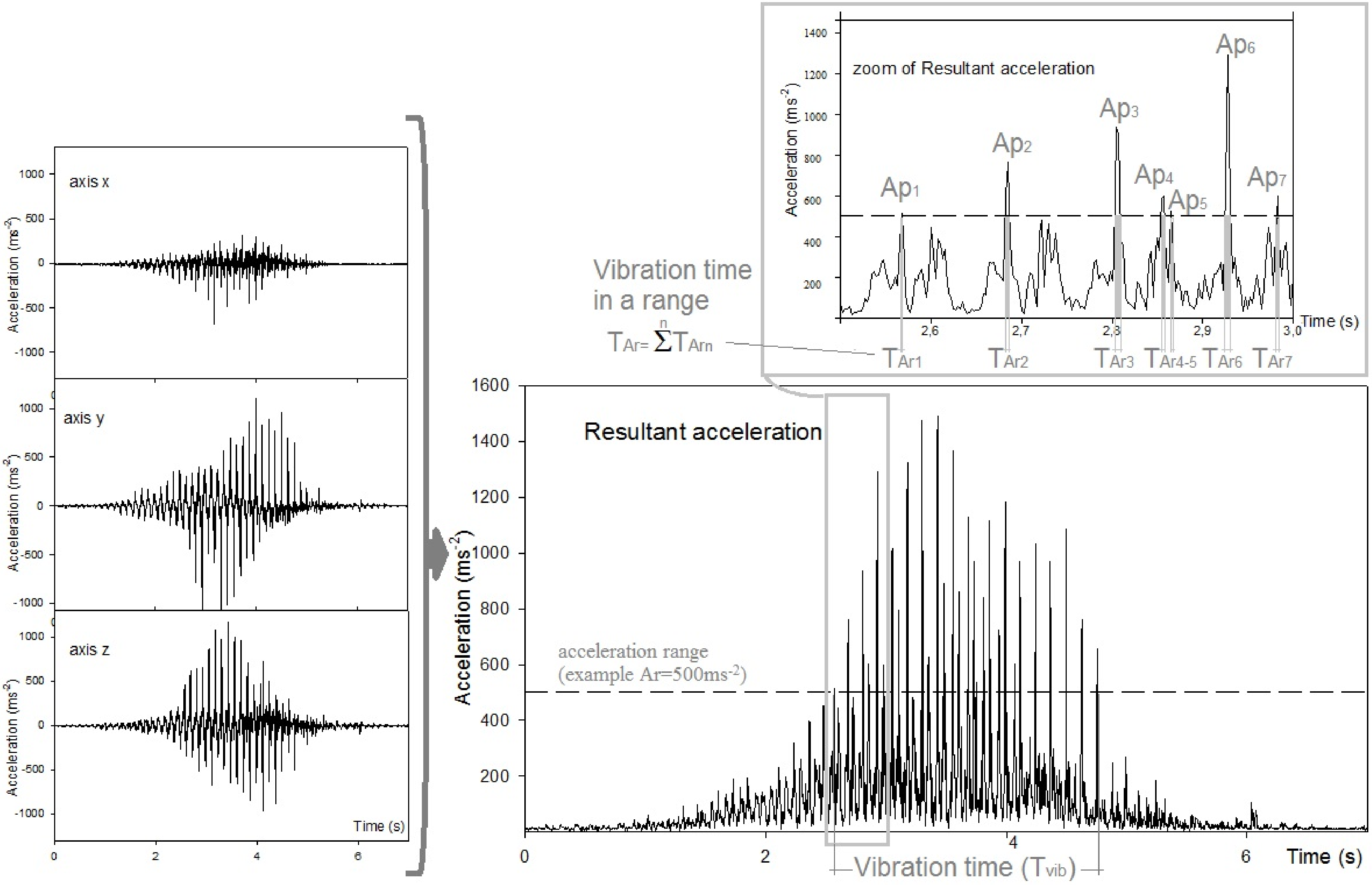
Table captions

Table 1. Some vibration parameters of the plot tested, separated in two groups according to cluster model.

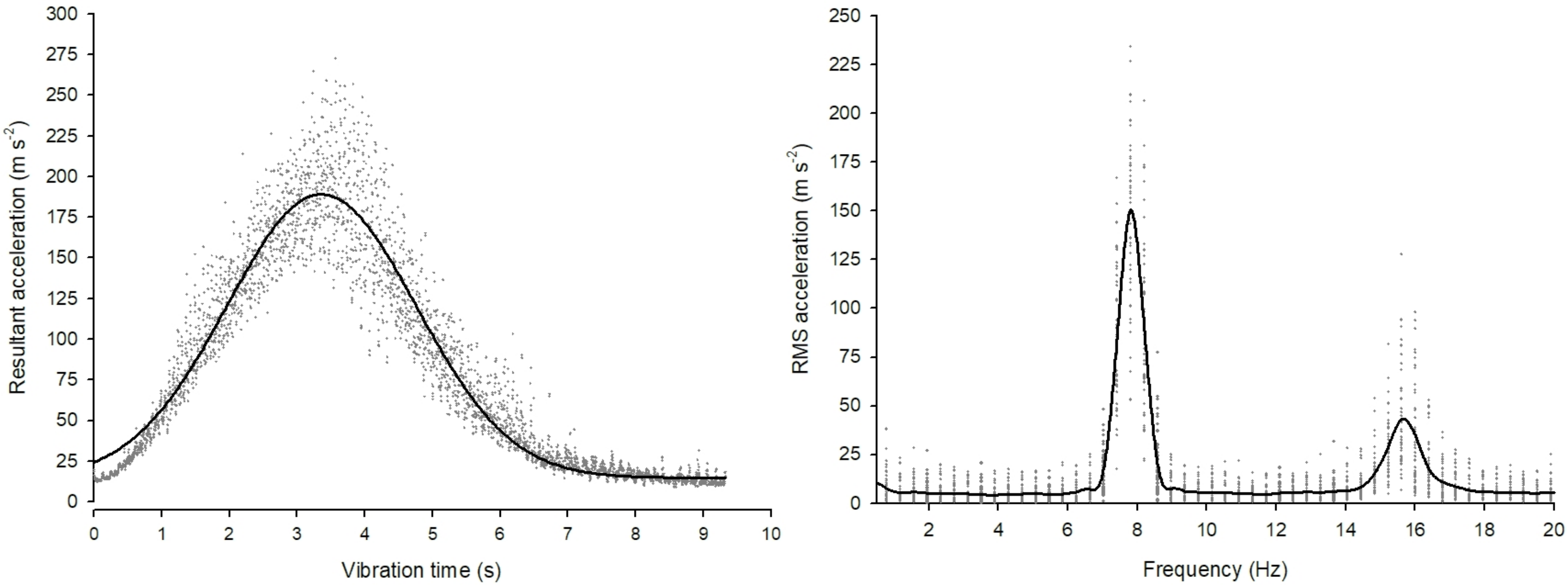
Parameter	Group	Min	Max	Mean	CV (%)
Distance from the ground (Height) (m)	1	1.50	2.40	1.88 a	12.5
	2	0.65	1.70	1.09 b	26.3
Peak acceleration (A_p) (m s^{-2})	1	707	1607	1282 a	19.0
	2	276	1076	717 b	35.0
RMS acceleration (A_{RMS}) (m s^{-2})	1	90	165	128 a	13.8
	2	35	118	78 b	25.4
Vibration time (T_{vib})(s)	1	5.30	8.90	6.94 a	15.6
	2	4.80	9.33	6.75 a	16.2

Values for a variable followed by the same letters are not significantly different (t Student, $p < 0.05$)

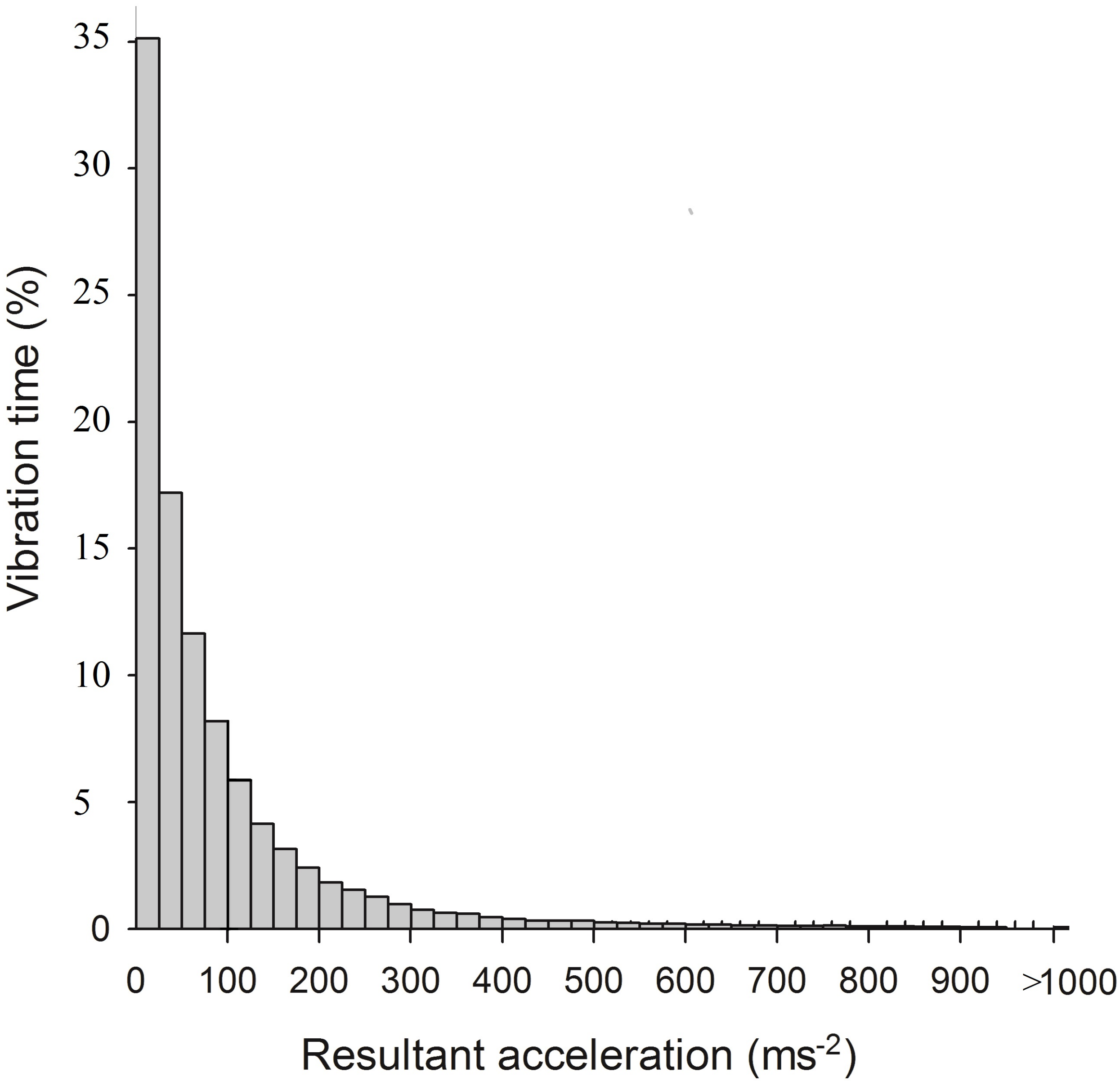
Ground forward
Z
Y
X



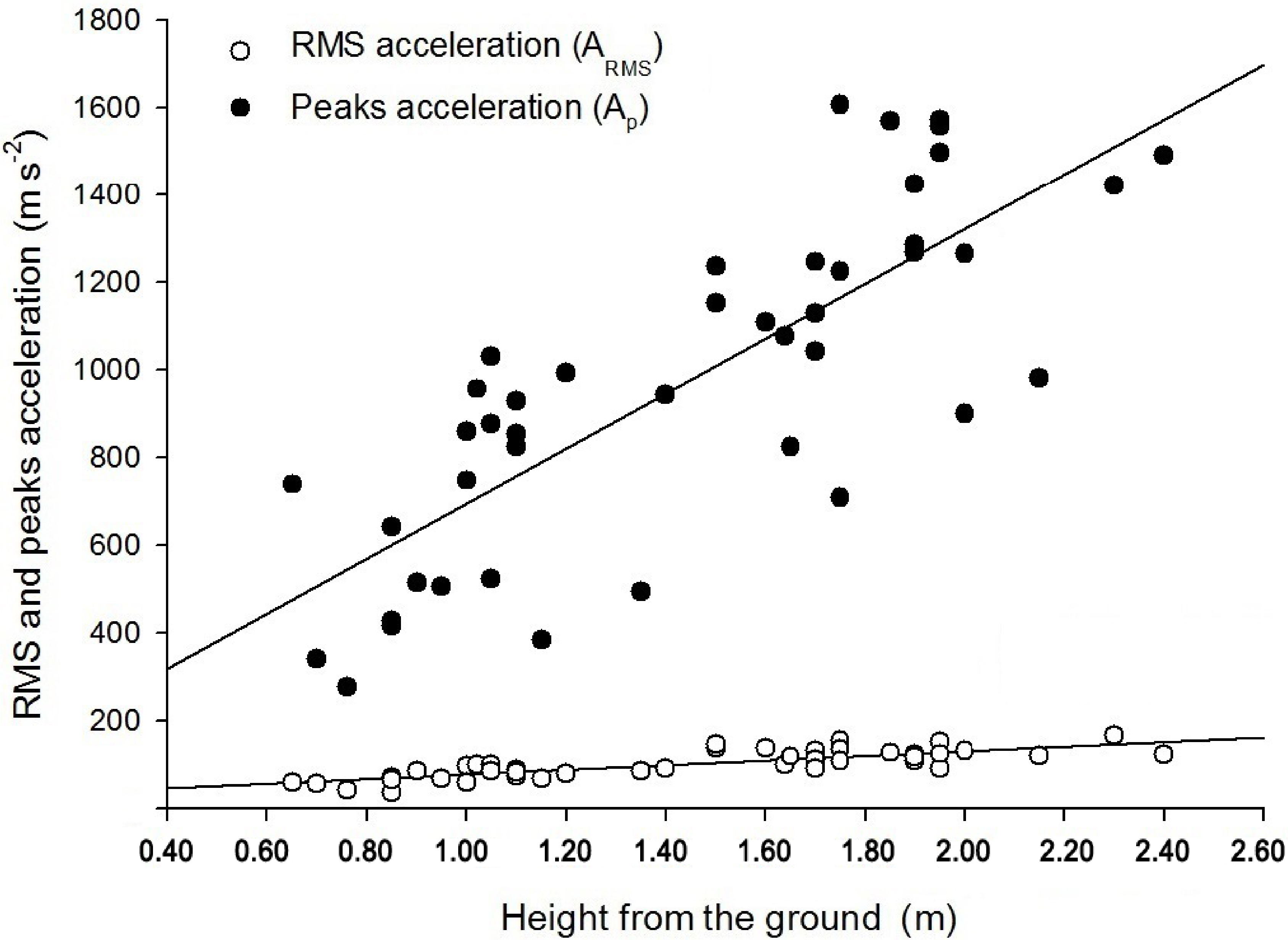
axis x
axis y
axis z
Acceleration (ms-2)
Time (s)
Resultant acceleration
zoom of Resultant acceleration
Ap1 Ap2 Ap3 Ap4 Ap5 Ap6 Ap7
TAr1 TAr2 TAr3 TAr4-5 TAr6 TAr7
Vibration time
in a range
TAr= ΣTArn
acceleration range
(example Ar=500ms-2)
Vibration time (Tvib)

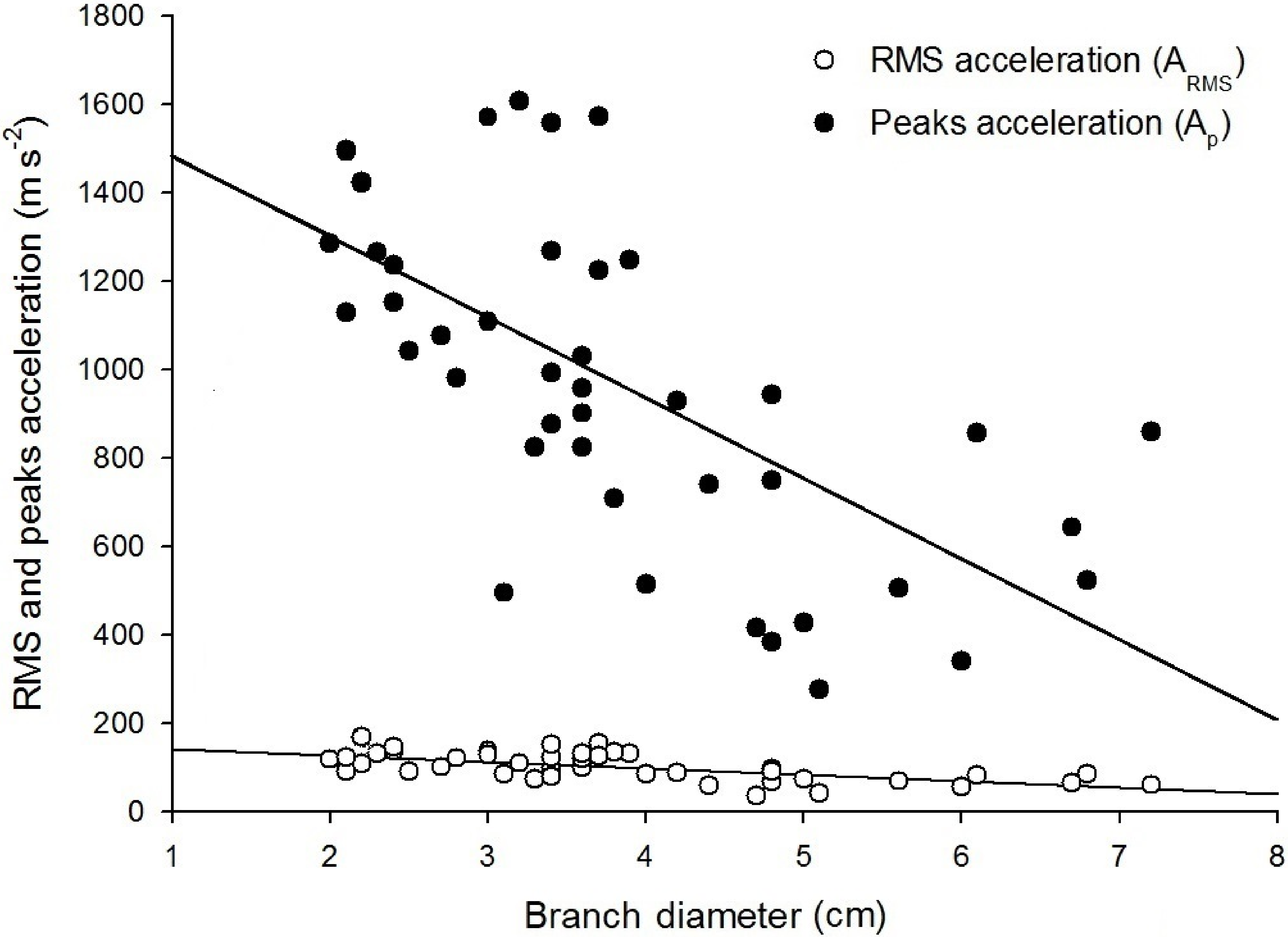


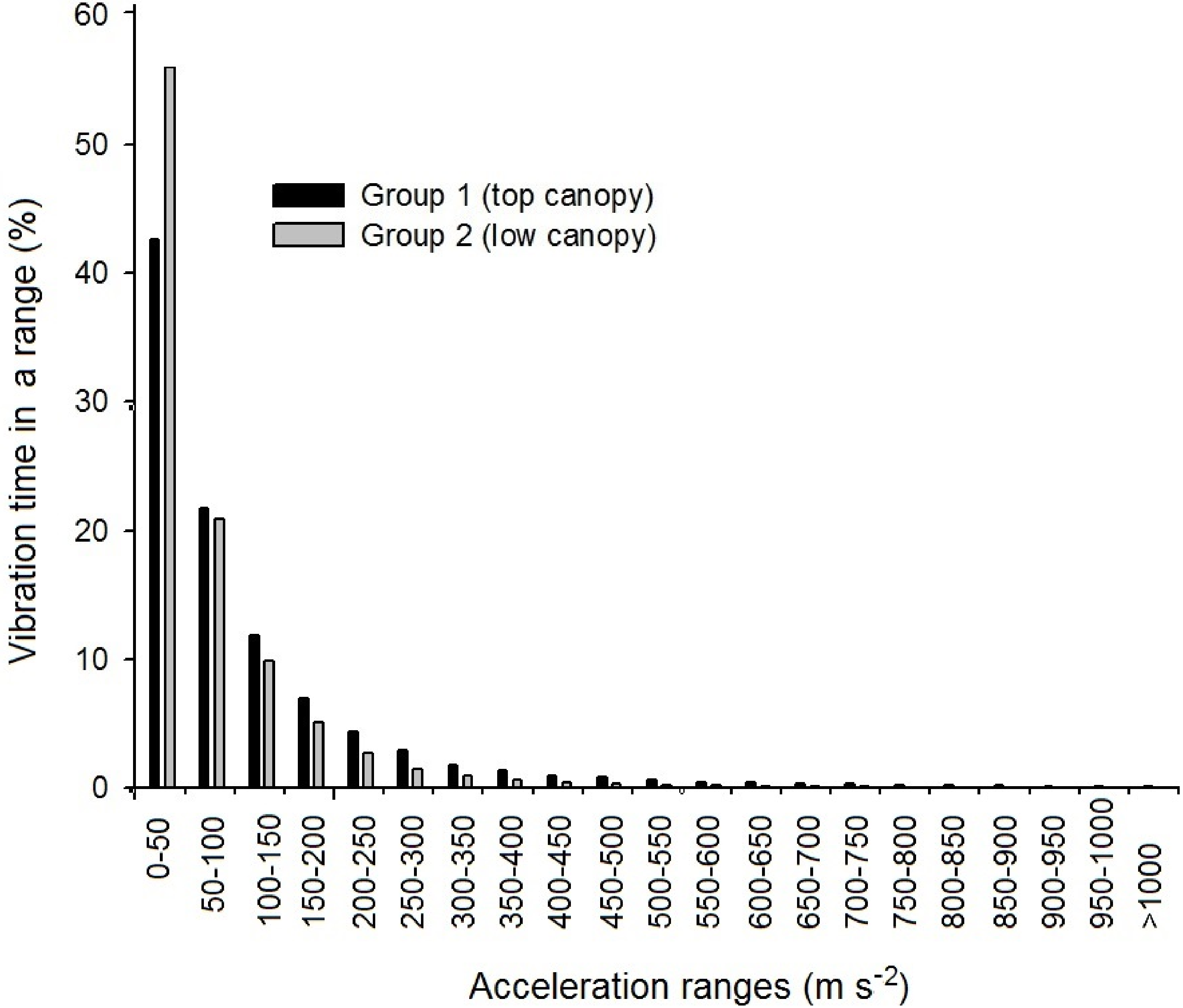
Resultant acceleration (m s-2)
Vibration time (s)
RMS acceleration (m s-2)
Frequency (Hz)



Vibration time (%)
35
30
25
20
15
10
5
0
0
100
200
300
400
500
600
700
800
900
>1000
Resultant acceleration (ms^{-2})


RMS acceleration (A_{RMS})
Peaks acceleration (A_p)
RMS and peaks acceleration ($m\ s^{-2}$)
Height from the ground (m)
1800
1600
1400
1200
1000
800
600
400
200
0.40
0.60
0.80
1.00
1.20
1.40
1.60
1.80
2.00
2.20
2.40
2.60


RMS acceleration (A_{RMS})
Peaks acceleration (A_p)
RMS and peaks acceleration ($m\ s^{-2}$)
Branch diameter (cm)
0
200
400
600
800
1000
1200
1400
1600
1800
1
2
3
4
5
6
7
8



Vibration time in a range (%)
60
50
40
30
20
10
0
Group 1 (top canopy)
Group 2 (low canopy)
0-50
50-100
100-150
150-200
200-250
250-300
300-350
350-400
400-450
450-500
500-550
550-600
600-650
650-700
700-750
750-800
800-850
850-900
900-950
950-1000
>1000
Acceleration ranges (m s-2)