Assessment of aerial and underground vibration transmission in mechanically trunk shaken olive trees

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Abstract

The present study analyses the transmission of vibrations generated from a multidirectional trunk shaker to olive tree structure considering both the aerial zone (trunk and branches) and the underground zone (the coarse root). The vibration characterization was conducted by measuring acceleration on several points of the tree during harvesting operations. The influence of two different heights of shaker head clamping was analysed. In addition, a dynamic probing was performed in order to evaluate soil compaction. The results showed that the vibration performed by the trunk shaker head, corresponding to an acceleration resultant of approximately 77 ms^{-2} with a dominant vibration frequency of 18 Hz, increased up to 106% in branches and decreased up to 90% in trunks. At root level, where the analysis was carried out at 1/3 and 2/3 of the coarse root length, the acceleration values diminished significantly to 17 ms^{-2} and 12 ms^{-2}, respectively. Soil dynamic resistance was lower (36 kg cm^{-2}) near the trees than between the trees (53 kg cm^{-2}). The vibration transmission to the aerial and the underground parts diversely influences the dynamic behaviour of the olive tree, considering an operational frequency of a commercial trunk shaker. The assessment of vibration transmission to the aerial part could contribute to improve fruit detachment and reduce branch breaking and leaf detachment. While vibration transmission to the underground part rises new challenges considering soil compaction in olive groves.

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Introduction

The olive sector plays an important role from economic and social points of view (Duarte *et al.*, 2008; Crisosto *et al.*, 2011). Indeed, olive cultivation is spread over 10.6 million ha in the world, among which, 24% is cultivated in Spain and 11% in Italy (FAOSTAT, 2016). In Calabria (southern Italy), olive orchards for table olives and olive oil productions, are spread over 183,000 hectares and produce more than 75,000 tons of oil per year (ISTAT, 2016). This heritage is of noticeable importance; however, it is characterized by a high variability, due to the co-existence of extensive orchards with only few trees per hectare and intensive orchards having more than 600 trees per hectare (Famiani *et al*., 2014; Bernardi *et al*., 2018). Harvesting is one of the most important agricultural practices and may represent the most expensive one (Bernardi *et al.*, 2016).

To decrease harvesting costs, it is necessary to improve productive capacities of the employed machines in harvesting operations. Technological innovation aimed to increase harvesting operation sustainability constitutes one of the most important points in allowing for the enhancement of olive growing.

Trunk and branch shaking is the most widespread technique used in olive harvesting from the tree. Canopy shaking machines were developed to be employed in traditional olive orchards, rather than trunk shakers (Sola-Guirado *et al*., 2016).

The main purpose of tree shaking is to transmit the acceleration to the bearing branches causing fruit detachment. The vibration is supplied by shaking the branches or the trunks at appropriate points and with appropriate shaking characteristics for each fruit tree (Srivastava *et al*., 2006). Theoretical works to determine the optimal characteristics of shaking have been completed (D'Agostino *et al.,* 2008; Castro-García *et al.*, 2014) considering the effect of the applied acceleration at several points along the branches (Zhou *et al.,* 2016) or the trunks (Aristizabal *et al.,* 2003). However, there is a gap in the study of vibration effects upon the whole tree including its roots.

The olive root system is composed of a skeleton of few primary structural roots from which secondary and lateral roots with decreasing diameter are generated. This root system develops within the first 0.60-0.70 m of soil and reaches 1 m depth and approximately 0.30-0.40 m around the trunk (Chiraz, 2013). The system is dependent on soil features and among them its dynamic resistance. Many relationships between root anchorage and tree characteristics have been studied in order to predict the resistance of a tree to uprooting (Dupuy *et al*., 2007; Khuder *et al.,* 2007).

Studying the influence of vibration on roots has been of interest in several cases such as tree uprooting in forests due to wind (Nicoll and Dunn, 2000) as well as in fruit trees to prevent root damage (Láng, 2008). The possibility to simulate the natural tree behaviour under different shaking conditions (Castillo-Ruiz *et al.*, 2015) would be helpful to test and, therefore, to improve the machinery performance. The development of artificial trees (patent SU 1024781; patent CN 203053919 U), which include the root system, could provide a valuable tool to evaluate the same trees under different harvesting parameters.

The objective of this study was to determine the vibration transmission from a trunk shaker to the whole tree, considering both the aerial zone (trunk and branches) and the underground zone (the coarse root) during olive mechanical harvesting. Furthermore, soil dynamic resistance was analysed in order to assess the vibration transmission to the radical system during mechanical harvesting with trunk shaker. The output of such an analysis could be useful to investigate other aspects: *e.g.* root growth and trafficability.

Materials and methods

Tests were conducted in an intensive irrigated commercial olive orchard (*Olea europaea* L. cv. *Carolea*) in Reggio Calabria, southern Italy (Lat. N 38°23'18.6", Long. E 16°04'14.8") in October 2015. Weather conditions were similar during the whole period of the trials. The tested trees, whose dimensional parameters are reported in Table 1, were vase-shaped with good physiological and health conditions.

The modulus of elasticity

The modulus of elasticity (MoE) was evaluated in 20 trees using a TreeSonic (FAKOPP's, Hungary) to determine vibration transmission in the trees according to their diameter (greater and smaller than 0.31 m). The stress wave time considering the wood fibre length was calculated according to Bragato (2014), with a wood density (δ) equal to 920 kg m^{-3} (Francescato *et al.*, 2009) and a wave propagation speed (V) determined at a distance of 1 m.

Frequency and acceleration measurement

The employed trunk shaker was a Sha Dedalus (De Masi s.r.l., Italy) with a multidirectional-type vibration pattern, that is, two eccentric masses rotating in opposite direction but with a close rotation speed values. The clamping system configuration has two contact points between trunk and machine, with one fixed arm, and rubber pad system. Field tests were carried out with an intermediate wear level of the pad system, which still provide a fixed clamp to the trunk. The trunk vibration process was performed with the motor machine throttle fixed to reach 2200 rpm and 200 bar of oil pressure in order to reduce the variability of the tree excitation parameters. Trials were conducted on randomly chosen trees and the vibration was applied at two different heights on the trunk: 0.44 m (low clamping) and 0.88 m (high clamping) (Figure 1). The same vibration duration (8 seconds) was applied to all tested trees, maintaining the shaker throttle constant in order to avoid its influence on the measured parameters.

A series of tests were performed to characterize the vibration path along the tree structure during shaking. Triaxial piezoelectric accelerometers (PCB, SEN021F) were located at different points (Figure 2), in the aerial and the underground zones of the trees. Accelerometer position, considering both clamping heights, was the same for all the shaken trees.

One accelerometer was set on the shaker head near the eccentric masses with adhesive mounting. In the aerial zone, one accelerometer was set on the trunk at 0.66 m aboveground with screw mounting. The two clamping heights were at 0.22 m above and below, respectively, the trunk sensor. Another accelerometer was placed on the main branch having 0.11±0.03 m diameter, at a mean distance of 1.34 m from the shaker, corresponding to nearly 1/3 of the canopy diameter. The accelerometers were mounted on the adaptors (HD2030AC.1, Delta Ohm) and fixed to the main branches and roots with plastic strips. In the underground zone, two sensors were set at 1/3 and 2/3 of the coarse root length, corresponding, to 0.38 m and 0.85 m, respectively, from the trunk. At these points, coarse root diameter varied from 0.038±0.021 m to 0.021±0.01 m. (Figure 3). The root was partially uncovered in order to place the accelerometers at the two previously cited points. The sensors were then protected by a plastic film, and covered with the same quantity of the removed soil and compressed to simulate the initial soil compaction conditions. The measurement of the vibration was performed according to a reference system parallel to the ground that corresponded to the shaker plane, composed by a longitudinal *y*-axis and a transverse *x*-axis, as well as the *z* vertical axis.

Figure 1. Clamping height of the trunk shaker used in the tests.

Table 1. Tree dimensional parameters at the analyzed harvesting sites (means ± SE). The canopy volume was calculated according to the International Olive Council method (2007).

Planting layout (m)	Age (year)	Trunk Ø (m)	Trunk height (m)	Canopy volume (m^3)	Plant height (m)	Branch number (n)
6x6	25	0.31±0.03	1.33±0.10	82.68±35.61	4.86±0.7	3

Signals were recorded at a frequency ranging from 0 to 400 Hz with a sampling frequency of 1.28 kHz using a dynamic signal analyser (OROS OR35 integrated multi-analyser). Subsequently, they were analysed by fast Fourier transform with 401 lines of resolution using NVGate 8.00 software. The root mean square acceleration was calculated for vibration dominant frequency value (ω) using the resultant acceleration value (Ac_{3D}), as the vector sum of the three axes (x, y, z) measurements on each sensor. The acceleration transmissibility (A.t.) was calculated, for vibration dominant frequency value, as the ratio between the resultant acceleration value of the different measurement points on the tree and the resultant acceleration value of the shaker. An A.t. greater than one indicates vibration amplifications; otherwise, there is a vibration reduction.

Soil dynamic resistance

To evaluate soil compaction, a dynamic probing was conducted, with a dynamic cone penetrometer, category DL030 10 - medium according to DIN 4094 Part 1 and Part 2. The cone tip was inserted into the soil by dropping a hammer to consecutive depths of 0.10 m. The necessary number of blows to reach the most occupied layer of the root system (0.6 m depth) was counted. Dynamic probing was effectuated considering four distances (0.4 m, 1.6 m, 2.8 m, and 4.20 m) from the shaken tree towards the next two non-shaken trees. Then, soil dynamic resistance was calculated applying the *Dutch formula* that is specific to the used instrument (Sanglerat, 1972).

Furthermore, the main physico-chemical properties of the soil was analysed to characterize the field where trials were performed. These included soil texture and structure according to Boujoucos (1962); humidity content according to D.M. 13/09/1999 (Italian Regulation, 1999) and organic carbon content according to Walkley and Black (1934).

Figure 2. Set position of accelerometers: Trunk shaker head (0), main branch (1), trunk (2), 1/3 coarse root (3), 2/3 coarse root (4).

Statistical analysis

Paired t-test and one-way analyses of variance (ANOVA) were applied to the data to determine the presence of significant differences (Duncan's multiple range test, significant level $P<0.05$). Free R software version 3.1.2 (The R Foundation for Statistical Computing Platform) was used for data processing.

Results

The MoE in the trunk trees showed a mean value of 5.07±0.21 GPa. Statistical analysis did not reveal any significant difference of the MoE according to the considered diameter classes (T-test, $P>0.05$).

The multidirectional trunk shaker generated a sinusoidal vibration with two frequencies close in values. Figure 4 shows a representative signal of trunk acceleration in time and frequency domains in one direction of the horizontal plane (*x, y*). The resultant acceleration values in the different parts of the shaken trees

Figure 3. Accelerometer position on tree coarse roots.

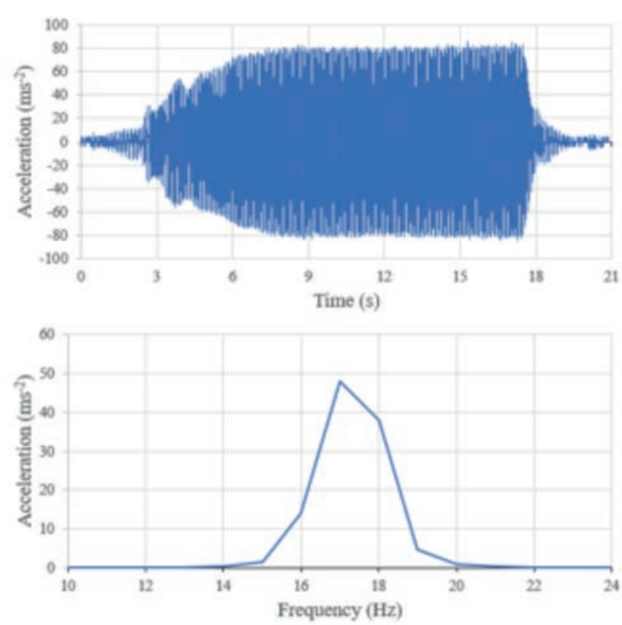

Figure 4. Sample of trunk acceleration signal in time domain (above) and frequency domain (down) measured in a direction perpendicular to the olive tree trunk.

and the machine are reported in Table 2. The trunk shaker performed a vibration with a mean frequency of 18 Hz and a resultant acceleration of approximately 77 ms^{-2}. The vibration frequency showed a low value of the coefficient of variation (<7%) during field tests. This variation was probably caused by the manual throttle control that could influence the pump flow and the hydraulic motor speed, and the own variation of the mechanical impedance of different tested trees. Both clamping head heights generated elevated values of acceleration in the aerial zone (branch and trunk) while the mean values of acceleration transmitted to the underground parts were substantially damped. However, the resultant acceleration considering all sampling points according to shaking height did not report any significant difference (Paired T-test, $P>0.05$).

Figure 5 shows that the acceleration values along the *x* and *y* axes are significantly different between the aerial (branch and trunk) and the underground zones (1/3 root and 2/3 root), considering both of the clamping head heights. On the other hand, the z-axis corresponding to the vertical direction presented acceleration values lower than the horizontal plane (*x* and *y* axes). In the *z*-axis, a clear differentiation was not obtained between the aerial and underground zones.

The vibration transmission from the shaker head to the different sampling points in the tree is shown in Table 3. The mean value of A.t. from the shaker head to the trunk showed an adequate value close to 1, with a mean value of 0.81 for low clamping and 1.03 for high clamping, but without significant difference between clamping heights.

The underground zone of the tree had a different behaviour towards vibration response with an important reduction in the acceleration transmission values, which corresponded to 0.23 at 1/3 of the coarse root length. This value decreased up to 0.16 at 2/3 of the coarse root length (corresponding to a distance of 0.85 m from the trunk to the sensor position along the root direction), showing that the acceleration transmission decreases as the distance from the clamping point increases. This trend matches the

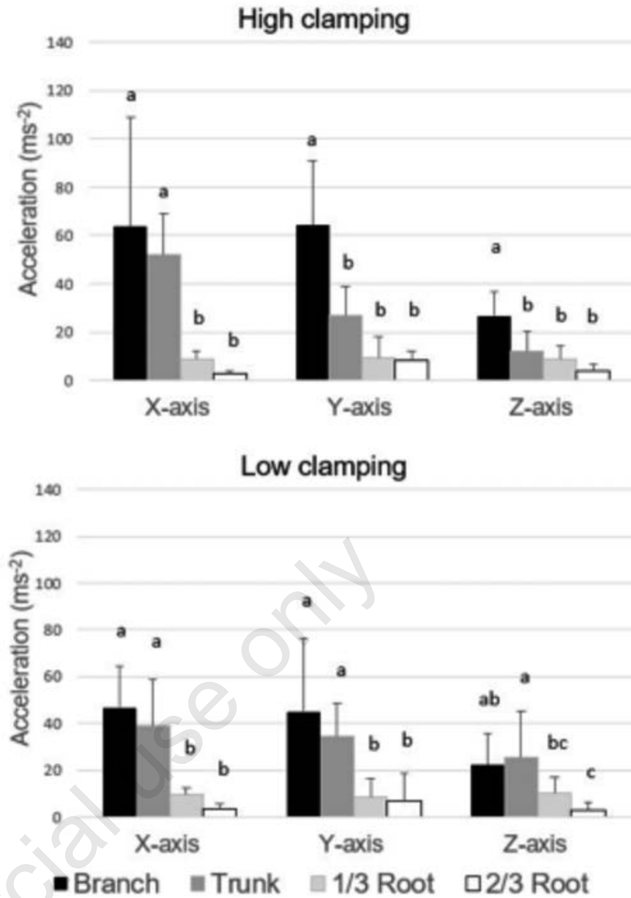

Figure 5. Analysis of variance of acceleration value referred to the clamping height. For each plot, results followed by different letters are significantly different by Duncan multiple range test (P<0.05).

Table 2. Resultant acceleration values according to the considered sampling points for both clamping head heights with a trunk vibration frequency of 18 Hz.

Tree zone	Sensor location	Acceleration (Ac_{3d}) (ms^{-2}) High clamping	Low clamping
	Shaker head	78.2±1.6[a]	75.6±2.1[a]
Aerial	Main branch	85.4±24.9[a]	80.9±35.2[a]
	Trunk	80.2±46.2[a]	61.5±23.26[a]
Underground	1/3 coarse root	16.5±7.4[b]	18.2±6.0[b]
	2/3 coarse root	10.0±5.2[b]	13.4±13.5[b]

Data are expressed as mean ± SD. Results followed by different letters are significantly different by Duncan multiple range test (P<0.05).

Table 3. Acceleration transmission from shaker head to the different sampling points for both clamping head heights.

Vibrations From	To	Acceleration transmission High clamping	Low clamping
Shaker head	Main branch	1.09±0.32[a]	1.07±0.47[a]
Shaker head	Trunk	1.03±0.60[a]	0.81±0.31[a]
Shaker head	1/3 coarse root	0.21±0.10[b]	0.24±0.08[b]
Shaker head	2/3 coarse root	0.13±0.07[b]	0.18±0.18[b]

Data are expressed as mean ± SD. Results followed by different letters are significantly different by Duncan multiple range test (P<0.05).

results related to soil dynamic resistance that decreases from the 0.4 m to 1.6 m sampling points (Table 4).

The analysed soil presented a sandy loam texture, a humidity of 14% and the organic carbon was equal to 2.54%. Table 4 reports the main soil geotechnical parameters, indicating soil compaction level, evaluated according to the D.M. 14/01/2008 at different distances from the shaken trees (Italian Regulation, 2008). One-way ANOVA analysis and the subsequent Post-hoc analysis, according to Duncan's multiple range test, showed that dynamic tip resistance is significantly influenced by the probing distance from the shaken tree with $F(3,92)=4.69$, $P<0.05$, $\eta p^2=0.137$; with lower mean values near the trees (both in vibrated and non-vibrated) than between the trees (at 1.60 m and 2.80 m). The sampling zones close to the trees present, therefore, a lower resistance to the metallic conic tip than those between the trees. This is furthermore confirmed by the Young's Module ($F(3,92)=7.87$, $P<0.05$, $\eta p^2=0.66$), which represents the ratio between the applied effort and the resulting deformation and the edometric modulus ($F(3,92)=12.14$, $P<0.05$, $\eta p^2=0.75$), which evaluates the previous deformation when the lateral expansion is impeded. In addition, relative density, unit volume weights, shear deformation and shear wave velocity presented low values, indicating that the soil included air making it difficult to the longitudinal waves, generated during the trials, to pass. Finally, the angle of friction of about 30°, indicating the friction shear resistance of soils together with the normal effective stress, was coherent with the texture characterizing the analysed soil.

Discussion

Olive tree green wood is highly anisotropic (Dahmen *et al.*, 2010), and green lumber is considerably more sensitive to temperature change than dry lumber (Green and Evans, 2008). Indeed, the experimental trials reported in this study were performed under a similar range of temperature (15-21°C; 76% relative humidity) and wood moisture of the shaken trees was similar as there was no debris in the trunk bark, as reported by Bentaher *et al.* (2013). The obtained results showed similar MoE mean values in the trunks indicating that the trees should have the same behaviour under vibration transmission.

Vibration frequency values transmitted to the trees, in this study, were lower than those reported by Leone *et al.* (2015) and Castro-García *et al.* (2007), who suggest applying an excitation frequency between 20 and 40 Hz during mechanical olive harvesting. However, the obtained values were more similar to those obtained by Ortiz and Torregrosa (2013) during fresh mandarin harvesting or by Abdel-Fattah *et al.* (2003) during almond harvesting. The acceleration results showed an ample dispersion of values for the same sensor location for each tested tree. The variation coefficient ranged between 37% and 90%. This indicates that the acceleration transmitted to different zones of the tree is highly related to tree structure and sensor location, according to the variation of the vibration path (He *et al.*, 2013). Several authors, even varying the vibration pattern of the shaker, have reported this behaviour (Abdel-Fattah *et al.*, 2003).

Regarding the effect of shaking head clamping position, Castro-García *et al.* (2015) suggest that a high clamping could increase the canopy acceleration, thereby enhancing fruit detachment. Nevertheless, it is necessary to take into account that large canopies may need more powerful machines, which are not always available for all farmers (Jimenez-Jimenez *et al.*, 2015). The acceleration values from each axis are influenced by several factors during the vibration process (Du *et al.*, 2012). It is therefore more suitable to use the resultant acceleration Ac_{3d} for vibration pattern characterization in the tree during harvesting (Sola-Guirado *et al.*, 2014). The results obtained in this study have shown a high variability of the resulting acceleration values in the measurement points of the tree (Table 2). Although the mean value of the A.t. to the branch has shown an amplification of the vibration from the shaker (Table 3), non-significant differences have been identified between clamping heights. In any case, to determine the effect of the clamping height, a greater number of trees together with an evaluation of the fruit removal efficiency with trunk shaker is required.

A.t. results may be a consequence of shaker design, clamp elastic padding material or limitation of the clamping force in order to prevent damage to the trunk bark. This should be taken into account because a low transmission rate may damage the padding material of the shaker head or the trunk bark. Aristizabal *et al.* (2003) have reported similar problems and concluded that the vibration pattern conditioned bark damage. In this context, Leone *et al.* (2015) reported that the acceleration transmitted from the clamping head to the trunk decreased approximately with 53% and 57% in two Apulian traditional olive orchards.

In the aerial zone of the tree, the A.t. was amplified (mean of 1.08) in the first 1/3 of the branch length, as found by several other authors (He *et al.*, 2013; Castro-García *et al.*, 2017) who investigated the enhancement of fruit removal efficiency using trunk shakers.

The variations in A.t. as a function of clamping heights is in

Table 4. Soil properties in the olive orchard evaluated.

	Distance from the shaked tree and sampling points (m)			
	0.40	1.60	2.80	4.20
Dynamic tip resistance (kg/cm^2)	33.81±22.02^a	51.49±27.01^b	54.83±27.07^b	35.48±19.91^a
Relative density (%)	11.22±1.30^a	17.92±6.66^b	15.80±0.50^c	12.04±2.07^a
Angle of friction (°)	27.48±0.13^a	27.91±0.22^b	27.95±0.05^c	27.57±0.20^{ab}
Young's modulus (kg/cm^2)	38.03±1.49^a	42.77±2.47^b	43.17±0.58^c	38.94 ±2.29^{ab}
Edometric modulus (kg/cm^2)	45.20±2.01^a	51.61±3.35^b	52.16±0.79^b	44.31a±2.57^a
Unit volume weight (t/m^3)	1.38±0.22^a	1.45 ±0.35^b	1.45 ±0.05^b	1.39a±0.36^{ab}
Shear deformation modulus (kg/cm^2)	101.81±26.90^a	185.31±42.98^b	192.54±10.13^c	117.89±41.04^{ab}
Shear wave velocity (m/s)	53.52±3.34^a	61.31±3.74^c	61.56±2.06^c	55.32±3.34^b

Data are expressed as mean ± SD. Results followed by different letters are significantly different by Duncan multiple range test ($P<0.05$).

line with data obtained by Horvath and Sitkei (2005), who noted that energy dissipation is high, especially in low clamping due to soil damping, as well as to tree canopy damping in the air. The transmitted resultant acceleration value increased by approximately 2% when the clamping head was positioned in the upper part of the trunk, rather than the lower part. High clamping reached a higher amplitude of vibration because it provokes a higher elastic deformation of the trunk demanding a lower power consumption (Horvath and Sitkei, 2001). The differences in transmission were very small when compared to more important limiting factors such as quality of clamping or shaker head features. In this way, the aerial tree geometry should be adapted to better transmit the vibrations.

The embedment of the tree into the soil was highly important in the vibration damping generated by the shaker. Indeed, the obtained results considering the roots, are in accordance with those of Horvath and Sitkei (2001), who reported that the vibrating soil mass has a large damping capacity. Indeed, the roots showed a high and quick damping of approximately 77% of the transmitted acceleration.

Moreover, soil analyses showed that the dynamic resistance was lower near the trees (both vibrated and non-vibrated ones) than between the trees (at 1.60 m and 2.80 m from the tree). This is probably due to soil compaction caused by machinery passage when carrying out diverse agricultural practices. These values indicate that the acceleration transmission from trunk to the furthest roots was conditioned by a major dynamic resistance of soil.

Conclusions

In order to improve trunk shaker efficiency, it is necessary to consider the agronomical conditions (tree architecture, canopy density, pruning), trunk shaker operational parameters (clamping location, clamping force) as well as the interaction between all these parameters, because it influences significantly the harvesting process. The employed methodology in this study, including the vibration transmission to the radical system, highlighted the existing differences in the vibration acceleration between the aerial and the underground zones of the olive tree.

Studying deeply the aspects related to the vibration behaviour in the radical system may be useful to develop more accurate vibration transmission models that could contribute to develop new and innovative harvesting systems to be employed in different conditions.

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