THE OPERATIONAL MODAL ANALYSIS FOR THE IDENTIFICATION OF FRUIT TREE STRUCTURES

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Abstract

Harvesting has a great influence on the costs of olive production. The workhours required for hand-made harvesting operations decrease from 75-83% to 50% of the human labour when shakers and nets are used for mechanical harvest operations.

Fruit removal is the main result of the impact that a vibratory fruit-harvesting machine produces on a fruit tree. The quantity of removed fruits under certain conditions and machine performance is a crucial practical indicator for the efficiency of the mechanized harvest.

In particular, trunk shakers are mostly used, in combination with convenient intercepting means on the ground or around the trunk, typically constituted by nets or by an upside-down umbrella. A multidirectional force (shaking) is applied to the trunk or to its branches. The resulting vibration causes the fruits to fall into the intercepting means.

Although a lot of work has been done on the mechanics of tree shakers, several fundamental problems still remain unsolved such as energy transmission along trunk and branches determining fruit detaching.

In this paper the use of operational modal analysis for the evaluation of the dynamic properties of fruit trees is investigated, pointing out the opportunities offered by these techniques to define an appropriate harvesting layout.

1 Introduction

Harvesting has a great influence on the cropping operations, with the highest impact on the costs of olive production. Several authors have been able to demonstrate that the workhours required for hand-made harvesting operations account for about 75-83% of the human labour utilized by this crop. When shakers and nets are used for mechanical harvest operations the above percentage decreases to 50%. The studies carried out are mainly focused on the vibration of the heads of the shakers in a order to increase the percentage of drupes falling down.

Fruit removal is the main aim of vibratory fruit-harvesting machines used on fruit-bearing trees.
Trunk shakers are mostly used in combination with convenient intercepting means on the ground or around the trunk, typically constituted by nets or by an upside-down umbrella.

Lots of researchers worked on shaker design and optimization both analysing fruit removal efficiency and tree damage. Adrian and Fridley [1] and Parchomchuk and Cooke [2] presented fundamental vibration theory and design criteria for different type of tree shakers. Parameswarakumar and Gupta (1991) [3] showed that, to obtain maximum fruit removal with minimum tree damage, the shaker should be operated in the range of 76–102 mm amplitude and frequencies of 11–13 Hz for 4 s. Horvath and Sitkei (2001) [4] proposed a tree model analysing different kinds of trunk motion. Based on acceleration measurements in the soil body, a new mass component was included, in addition to the common mass components. More recently, they investigated energy requirements showing that energy calculations often give lower values than true ones [2]. H. M. Abdel-Fattah et al. [5] used a vibration shaker driven by a variable speed electrical motor to reproduce and control vibration level along a single axis and introduced wavelet filtering to better estimate displacement by integration and main frequencies of the acquired signals. Erdogan et al. [6] studied harvesting of apricots by mean of an inertia type limb shaker. They analysed fruit damage and removal efficiency with respect to fruit mechanical properties and harvesting parameters.

L. M. Mateev and G. D. Kostadinov [7] presented a probabilistic model of the fruit removal in which the quantity of the non-removed fruits from the tree and the probability for an insufficient harvest duration decrease exponentially when the vibratory impact duration upon the tree increases, despite the differences in harvesting conditions. Sessiz and Ozcan [8] carried out harvesting of olive by pneumatic branch shaker and abscission chemical. The maximum harvesting efficiency (96%) was achieved at 24 Hz and 6.25 mL/L of abscission chemical concentration.

Lang [9] described mathematically the power consumption, generated amplitude and specific power for each trunk under test using a tree structure model which comprises both trunk and main roots. Finally, Sanders [10] presented an interesting review about mechanical harvesting methods used for orange trees but applicable also to other type of trees.

On this basis it is well known that fruits suddenly fall, especially within the transient when frequency span technique is used, periodically accelerating and slowing down the shaker. In particular, olives harvesting is characterized by scalar ripening: therefore, those not immediately detaching drupes hardly fall shaking on and on. In some cases better results are obtained stopping shaking, opening the claws, and moving the shaker in another position with respect to the trunk in order to shake it along a different direction. Another solution consists in shaking directly the branches which, for particular geometric shape and physical properties, are not sufficiently affected by the vibration. In order to avoid multiple shaking, multidirectional shakers are used. In fact, investigations about the precession motion of the main mode showed that it is too slow, requiring a long shaking time to complete the rotation.

Although a lot of work has been done on the mechanics of tree shakers, several fundamental problems still remain unsolved, such as energy transmission along trunk and branches determining fruit detaching and influence of basic tree dynamic properties on the efficiency of different shaker layouts.

In this paper the use of operational modal analysis for the evaluation of the dynamic properties of fruit trees is investigated, pointing out the opportunities offered by these techniques to define an appropriate harvesting layout.
2 Typical harvester layout

The harvester is made by a tractor, a hydraulic power pack, divided into the following parts (Figure 1):

- the pump and the tank, usually on the rear of the tractor, and the hoses connections with directional valves on the front;
- a telescopic extensible arm fixed on the tractor front, with a rotating chassis on its upper end, that carries beneath it the vibrating head, suspended by three chains;
- the shaker, in which a sinusoidal oscillation is generated by means of a couple of eccentric rotating masses, moved by two hydraulic motors;
- the gripping clamps, that are used to grab and transmit the vibration to the trunk.

In particular, the shaker has two slightly different eccentric masses rotating in opposite directions at almost the same speed, developing multidirectional shake.

One of the main disadvantages related to the use of this equipment is a great power consumption; moreover, the plant can suffer damages. Finally, non-linear effects due to the high level of vibrations occur, as shown in Figure 2.

Horvath and Sitkey [4] have shown that, when fruit trees are shaken, the damping losses may be very high, depending on the height above ground at which the shaker is attached to the tree trunk. This conclusion was based on energy measurement for several trunk shakers. In particular, the high damping losses were explained by the fact that, during shaking, a given soil and root mass is also taking part into vibration. The soil, especially at large shaking amplitudes, has an increased damping ability and is the most important energy absorber of the whole system. As a consequence, the net power consumption of the shakers can be nearly the same as the theoretical power capacity of the vibrating system, because the high damping losses consume most of the net power.
On this basis, a specific study has been started aiming at an optimization of the power consumption of the shaker during harvesting. To reach this goal an appropriate investigation of the dynamic properties of trees and a simple model of their behaviour under dynamic loads are fundamental: in fact, they can be useful to define the “best” location of the shaker along the trunk, that is to say the most efficient one in terms of power consumption, and the most appropriate values of frequency and amplitude of vibrations to optimize the harvesting operations.

3 Dynamic properties of fruit trees: a literature review

The size of trees and their architecture greatly influence their dynamic behaviour: in particular, as tree grows, the added biomass develops a greater self-loading. Moreover, the effect of branches, which dampen the motion of the tree as a whole, has to be considered.

Whitney et al. [11] proposed a model of the tree trunk as a cantilever beam and they found that it absorbs very little energy, acting nearly as a pure spring.

However, the presence of branches has to be taken into account. Modifications to the previous simple tree model include representing the canopy as a lumped mass on a column [12], representing the tree as two masses (one for the canopy and one for the root-soil system) linked by the trunk modelled as a weightless elastic column [13], and modelling the tree as a series of n logs with lumped masses representing branch whorls along the trunk [14].

These simplified models do not consider the dynamic interaction of branches, which can be seen as dynamic coupled cantilevers and not simply as lumped masses [15].

Experimental investigations of the dynamic characteristics of trees have been also carried out by a number of authors [15-31]. Two main methods have been used: pull and release tests and tree sway measurements under real wind conditions.
A single forest tree (P. sylvestris) under actual wind conditions was monitored by Hassinen et al. [25]. Spectral analysis (Fast Fourier Transform) was used to evaluate the tree’s frequency response and showed preferred peaks at 0.2 and 1.85 Hz.

Baker [24] measured sway motion of 62 urban trees, with different heights, finding low frequency peaks between 0.3-0.6 Hz in summer and 0.5-1.5 Hz in winter.

Other investigations regarded the interaction of trunk with branches. Moore and Maguire [30], in particular, described the effect of branch removal on sway frequency. They showed that changes in natural frequency with crown removal did not appear to be due to changes in damping ratio, but rather to changes in mass distribution of the trees. They further suggested that representing the crown as a series of lumped masses as they did in their model might not be appropriate and further work is required to model the branches of a tree as individual damped harmonic oscillators coupled to the main stem.

James et al. [32] observed that each branch is a mass that sways in the wind and dynamically interacts with other branches and the trunk in a complex way. This interaction among the components of the crown introduces several frequency components in the spectrum of the tree and the natural frequencies tend to be buried, making identification difficult. Thus, they proposed a model consisting of dynamic masses representing the trunk, the main branches and the subbranches. Each structural member was considered as an individual oscillating mass attached via a spring and a damper to its base (the trunk is attached to the root-soil system, the main branches are attached to the trunk, and so on). The smaller branches, characterized by a small mass, were taken into account because they affect the dynamic performance of the tree with their contribution to (aerodynamic) damping. In this model the spring constant was related to the Young’s modulus of the material, while the damping factor was a complex quantity consisting of aerodynamic damping (energy dissipation by movement through the air) and viscoelastic damping (energy dissipation from internal factors). Various tests were carried out to calibrate this model, resulting in an interesting database for different types of trees (Table 1).

<table>
<thead>
<tr>
<th>Type</th>
<th>Frequency [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Washingtonia robusta</td>
<td>0.28</td>
</tr>
<tr>
<td>Cupressus sempervirens</td>
<td>0.26 - 0.66</td>
</tr>
<tr>
<td>Pynus sylvestris</td>
<td>0.2 - 1.85</td>
</tr>
<tr>
<td>Araucaria cunninghamii</td>
<td>0.29 - 0.40</td>
</tr>
<tr>
<td>Eucalyptus teretecornus</td>
<td>0.32</td>
</tr>
</tbody>
</table>

Table 1 Fundamental frequencies for different types of trees

As main result this study showed that dynamic tree sway in winds appear to be greatly influenced by the dynamic sway of the branches. As the proportion of branch mass to trunk increases, the natural frequency of the trunk become less dominant. Moreover, the branches act to dampen or detune the whole structure. So, the multiple tuned mass dampers concept, proposed by Abe and Fujino [33] in earthquake engineering literature, has been applied also in the modelling of fruit tree structures.

Less investigations have been carried out to determine damping. Hoag and Friedly [34] gave values between 0.06 and 0.08 obtained from specimens cut from the trunk. Moreover, external damping due to the air resistance of the vibrating canopy was investigated and found to be low in presence of low velocity of the canopy.
4 Environmental tree vibration

An experimental investigation to determine the dynamic properties of olive trees has been carried out and briefly reported herein: in particular, preliminary results of a test on a young tree will be shown. The tree vibrations due to intense wind were monitored for three hours. The obtained records have been used to identify the main modal parameters of the tree.

As shown in Figure 3, a whole tree, with trunk, main branches, subbranches and canopy has been tested, aiming at investigate the effects of canopy and, consequently, of aerodynamic damping on modal parameters identification. Other tests have to be carried out to study the dynamic behaviour of the tree in different configurations (only trunk, trunk and main branches, and so on): the aim is the evaluation of the effects of the canopy mass on the main frequency.

The dynamic response of the tree has been measured along the trunk and on the main branch. Nine Force Balance accelerometers (Kinematics EpiSensor ES-U2) have been placed: in particular, they were installed, in groups of three sensors, along two orthogonal directions at three different heights. The axis of the trunk was orthogonal with respect to the directions of the sensors. As regards the accelerometers characteristics, they have a bandwidth (-3 dB) of about 200 Hz at 1 g, a full scale range of ±1 g, 2.5 V/g as sensitivity and a negligible mass with respect to the tree. A Kinematics K2 Digital Recorder, characterized by a 24-bit DSP, has been used for data acquisition.

The tree vibrations were measured for about three hours, characterized by intermittent wind rushes. The sampling frequency was 100 Hz. In Figure 4 some accelerations records are reported.
Analyses in the frequency domain were performed through a software developed by Rainieri et al. [35] in LabView environment: in particular, output-only identification in the frequency domain was carried out using an Hanning window to reduce leakage, and with a 66% overlap.

**Figure 4 Acceleration records**

5 Signal processing and relevant results

A preliminary evaluation of the modal parameters of the tree has been carried out using the Basic Frequency Domain approach [36]. The computed spectra showed a first natural frequency at about 1 Hz (Figure 5). Before applying the Fast Fourier Transform algorithm to the computation of the power spectra, the records were analyzed through the Short Time Fourier Transform (Figure 5). The STFT showed that, even if an intense wind loaded the tree, as witnessed by the acceleration peak of about 7 cm/s², no non-linear effects occurred. Thus, according also to the various studies reported in literature, the tree can be considered as linear and elastic and the identification
algorithms can be applied.

A more refined analysis was carried out based on the Enhanced Frequency Domain Decomposition approach [37], aiming at the identification of damping and mode shapes too.

From the entire record different portions were selected: in fact, analyses were carried out in presence of intense wind and on portions of record were the effect of wind was not too high, as witnessed by the lower values of acceleration.
As reported in James et al. [32], one of the main effects of the vibrating canopy was the introduction of several frequency components in the spectrum, so partially burying the resonances of the tree. Moreover, aerodynamic effects gave, as a result, complex singular vectors in correspondence of the selected peak on the singular values plots. Only in one case, the obtained mode shape was nearly normal, as shown by the complexity plot in Figure 6, and comparable to that one of a cantilever beam: it seems to be related to the lower influence of aerodynamic effects on the structure. However, deeper investigations are required on this matter. The lower influence of the aerodynamic effects has been highlighted by the possibility to estimate the damping ratio after having identified the SDOF Bell function and performed the Inverse FFT of the obtained spectrum. A value of 0.06 of the damping ratio for the first mode was obtained, in good agreement with those ones reported in the literature.

These preliminary results appear to be promising but other studies are required to evaluate the dynamic characteristics of the trees in different configurations or with different architectures. Moreover, deeper investigations on the effects of canopy on the dynamic behaviour of the tree have to be carried out, pointing out on the effects of complex mode shapes on harvesting operations. On the other hand, more advanced methods such as Stochastic Subspace Identification could be referenced to overcome some central aspects pointed out by the first results herein reported.

6 Final remarks and open issues

The present paper represent an example of cooperation between engineers analysing very different structural problems. In fact, fruit trees represent a quite complex system that requires careful evaluation in view of optimised and sustainable harvesting procedures.

More in detail, the attention has been focussed on olive trees that are common in large areas of Italy, and particularly in south-east, where large part of agricultural economy is related to olives and their transformation. Machines commonly used are generally not engineered and sometimes are not really effective, inducing damages to trunks and time-consuming olive removal sessions.

The interdisciplinary work has been therefore aimed at identify an alternative and innovative approach to the evaluation of dynamic properties of trunks and young olive trees without any
mechanical excitation.

Environmental vibrations of olive trees have been measured and analysed. Some interesting results have been obtained, particularly on the role of output-only identification methods like OMA.

Further developments are however needed to improve the knowledge of dynamic response of such fruit trees and above all to enlarge the availability of data concerning the dynamic properties of such structures for different configurations and types of excitations.

7 References

[1.] Adrian, P. A. and Fridley, R. B.: “Dynamics and design criteria of inertia type tree shakers”, Transactions of the ASAE, 8(1), 12–14, 1965


