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Numerical and experimental vibration analysis of olive tree for optimal mechanized harvesting efficiency and productivity

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ABSTRACT

A 3D model of a middle-size olive tree has been analyzed considering various shaking conditions by using an attached trunk shaker to improve the harvesting rate as regards the critical nodal acceleration and displacement. The effects of shaking frequency, loading type as well as temperature and loading height were simulated and investigated on olive-stem-twig joint rupture. Comparing the results of finite element modal analysis in ABAQUS 6.10 with those of field experiments, utilizing a hydraulic eccentric-mass trunk shaker, exhibits less than 5% deviation at frequencies between 10 and 25 Hz at the first four vibration modes with damping ratio of 16–30%. The experiments and simulations show the maximum harvested quantity of sample middle-size olive trees is 92% and 96%, respectively. It is acquired at $f = 20$ Hz, $T = 28$ °C for 45% moisture content of wood in late November 2012, without chemicals. The optimized mechanical harvesting yielded the lower number of workers, time saving (∼12 tree/h), and to improve the obtained productivity (293 kg/h). The results imply that accurate 3D analysis of mechanized olive harvesting can be an efficacious solution to obtain desired parameters and optimal efficiency, which is comparable to manual method.

1. Introduction

Mechanized harvesting process has drawn significant attention in recent decades as an unavoidable utility in order to cost reduction, time saving and speed up delivery of important agricultural crops like olives, cherry, apricot, almond, etc. Unaffordable and time-consuming hand picking is the main problem in traditional olive harvesting. In last decades, approaching to mechanized harvesting methods has been considerably grown. Although mechanized harvest approaches are widely implemented in many fields and orchards, less than 75% (per tree) of all crops are currently collected mechanically (Castro-García et al., 2014; Yousefi and Gholiyan, 2013) and therefore, there is still need to hire labors to pick the remainders on the tree. So, it is still needed to study the maximum efficiency of fruit harvesting by a more accurate modeling and analysis without abscission agents. In spite of the higher Harvesting Percentage (HP) reported for branch shaking machines or manual branch shakers (above 78%) (Yousefi et al., 2010), those methods are not time-efficient, cost-effective and protective against limb breakage as much as hydraulic trunk shaker. "Trunk Shaker" is one of the most important olive harvesting devices due to its simple eccentric rotational mass, variety of vibration patterns, more conventional usage compared with other methods, capability of linear or orbital loading and installing on traditional tractors (Sola-Guirado et al., 2014). Taking into account that mechanized harvesting increases the fruit damage index (Castro-García et al., 2015), the analysis and optimization process should facilitate the vibration transmission to the stem nodes on upper branches and protect the tree against breakage, rupture or delamination. The main objective of the present study is determining the optimum parameters of mechanized hydraulic olive harvesting in well-pruned orchards of Northern Iran to reach the maximum HP and productivity, simultaneously. The productivity is measured as collected fruit per hour (kg/h) per a single worker regarding harvesting period of each tree in a sample orchard. Conventional harvesting systems have some noticeable disadvantages like low HP, fruit bruising, stalk breakage, root and bark damages, leaf falling due to chemicals, etc. Therefore, an exhaustive optimization analysis of mechanized olive harvesting, which takes into account the

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most technical effective parameters, is promisingly expected to solve the main problems of conventional trunk shakers (Gezer, 1999). As many publications in this field is assigned to experimental studies (Farinelli et al., 2012a), simple 2D or 3D numerical simulations regardless of implementing temperature, wood orthotropic structure, humidity, linear loading, etc. (Bentaher et al., 2013; El-Awady et al., 2008), analysis of citrus trees (Savary et al., 2010; Yung and Fridley, 1975), investigation of different shaking methods (Yousefi et al., 2010), and study of detachment forces (Farinelli et al., 2012b), there is no reference in this field to be addressed considering the most effective parameters, entirely. In present research, Finite Element Analysis (FEA) is utilized to investigate the harvesting productivity of a real 3D structure with respect to the temperature and moisture-dependent behavior of elastic constants, load direction (linear and orbital) and loading height. The obtained results are compared with the experimental results in a designated well-pruned orchard as the representative for all similar circumstances to evaluate the average harvesting productivity.

2. Literature review

Adrian and Fridley (1965) investigated the vibrational behavior of a tree based on an unbalanced eccentric sinus loading, basic theory of vibrations and design criteria for various shakers in 1965. Yung and Fridley (1975) simulated an entire model of a tree and used FEA to study the vibrations in the whole system. In their report, mechanical properties of tree components were supposed to be elastic, homogenous and isotropic. At the same time, Keçecioğlu (1975) focused on an inertial mass shaker for olive harvesting and reported that olive tree should be vibrated 10 s at frequencies of 20–28 Hz with the wave amplitude of 20–30 mm to achieve the best harvesting efficiency. Near a quarter century later, Metzidakis (1999) reported the vibration effects on mechanical olive harvesting and inferred that mechanical vibration is not effective by itself to harvest more than 50% of total mass. Energy consumption of different shakers under various conditions was reported by Horvath and Sitkei (2001) who investigated the soil mass and damping properties in "tree-soil" vibration system. Sessiz and Özcan (2006) reported the efficiency of olive harvesting less than 50% using a pneumatic shaker without any chemicals and about 96% using chemical solutions at 24 Hz frequency. James et al. (2006) presented a model of tree in 2006 with specified dynamic characteristics of trunk and branches and showed the damping effect on reduction of tree oscillating movement. El-Awady et al. (2008) simulated a simple 3D branch of an olive tree in SAP2000 and analyzed its dynamic behavior regarding the mass and stiffness matrices. With respect to their results, top parts of an olive tree respond to frequencies near 22 Hz and displacement of 10 cm, while bottom portion does not react easily to frequencies above 14 Hz with less harvesting efficiency. They reported that loading height of 40 cm above the ground would have excited most branches and enhanced harvesting process. Green and Evans (2008) studied the effect of temperature between −26 and +66 °C and the Moisture Content (MC) on elasticity modulus of dry and wet wood and achieved the linear relationship between the increases of elasticity modulus with decrease of temperature. Dahmen et al. (2010) measured non-homogeneous engineering constants of anisotropic olive wood plates using air-coupled transducers generated Lamb wave and ultrasonic bulk wave. In the research work performed by Cicek et al. (2010) olive trees were harvested by four different methods. From the data obtained during a two-year period, the mechanical bough shaker + wood stick method was determined to be the one with the highest capacity. Savary et al. (2010) designed and optimized a canopy shaker and studied dynamic simulation of citrus trees beside field experiments. They determined the mechanical properties of the citrus tree wood under the assumption that it is isotropic in nature. Then, the acceleration data from the simulation were compared against the experimental data at 3–4 Hz frequencies. It is notable that the harvesting efficiency and productivity were not considered as their output results. Yousefi et al. (2010) compared pneumatic comb harvesting machine with branch shaking machine and hand picking. They believed that the mechanized method of harvesting has greatly improved the timeliness of operation, and the productivity of the labor. Moreover, productivity reduced as the fruit size and weight decreased. Di Vaio et al. (2012) and Famiani et al. (2014) determined the efficiency of mechanical olive harvesting with trunk shaker in southern Italy. The mechanical harvesting yield led to some advantages of low number of workers and reduced time for the operation which allowed a high productivity to around 302 kg/h per worker for 'Ortice' cultivar. Castro-García et al. (2014) studied and measured fruit detachment force (FDF) and tree geometrical characteristics by three triaxial piezoelectric accelerometers. In their work, HP varied from 56 to 87%. Although increased vibration power applied to trees for high level of canopy vibration improves harvesting efficiency, Castro-García et al. (2015) showed that it also implies an increase in fruit damage index especially in larger fruits with a positive linear relationship. One remarkable study was the one reported by Bentaher et al. (2013) who studied the stem shaking conditions in the mechanical harvesting of "Chemlali" olive fruits—the main variety in Tunisia—by undertaking a FE numerical modeling. They modeled an olive tree by 3D beams; Each beam had two nodes and 6 degrees of freedom for each node; The structure was built by 560 elements and 561 nodes. The Orbital and multidirectional (not linear) loading were tested and the excitatory force equation was developed as a function of the unbalanced mass, eccentricity and rotational frequency. Orbital loading was determined as preferable choice due to its higher reaction force. However, they did not perform any functional practice to compare their obtained results with their expected experiments. These inaccurate outputs cannot be justified regarding the experimental displacement and optimal productivity. A few papers are presently published on 3D modeling of olive tree structures. This study is significantly considering the important effective parameters such as anisotropic nature of olive wood, real 3D simulation, temperature and moisture-dependent behavior of elastic constants, load direction (linear and orbital), loading height, and harvesting productivity, together and simultaneously. Wood temperature and MC were measured using a non-contact digital infrared thermometer (DT-8380) and a pin-type Wagner wood moisture meter, respectively.

3. Materials and methods

3.1. Olive tree structure

The design of mechanized hydraulic harvesting machines is based on transmission of mechanical waves into the boughs as well as main branches, limbs, twigs, stems and nodes, which leads to orbital movement of fruits. It finally results in stem-twig or stem-fruit detachment and fruit dropping down (Di Vaio et al., 2013). The variable force applied to the fruit creates a momentum results in failure stress riser at the stem node, and if the force is large enough, the fruit will be detached. Attachment force of the stem to small branches depends on the different stages of fruit ripening. As the fruit further ripens, the harvest quantity rate grows highly (Ferguson et al., 2010). Using chemicals at harvesting time attenuates the attachment forces, causes vigorous mechanical harvesting and facilitates the fruit detachment. However, the use