Investigation of vibrational properties of apple, lemon and orange branches under dynamic loads

Amin Yazdanmanesh, Davood Kalantari

Abstract— **In the present research, investigation of vibrational properties of apple, orange and lemon tributaries is presented. Vibration of the samples were recorded by means of a digital video camera (Canon Sx 120IS) with 30 frames per second (fps). With reviewing the recorded frames in BsPlayer software, displacement of tip of the examined branches was measured and several vibrational characteristics were extracted or computed from the frames. Given the computed vibrational properties, a mathematical model is proposed for the free vibration of the apple, lemon and orange branches. Comparison between outputs of the model with the measurements indicates a good capability of the proposed model. The obtained results indicate that the orange branches have a significantly larger stiffness constant (k) and critical damping constant (c_c) in compare to the apple and lemon branches.**

Index Terms— **vibration, horticulture, stiffness, damping constant, shaker.**

I. INTRODUCTION

One of the most important phases of farming and horticulture is the harvesting operations. Harvest Time, appropriate methods of harvesting, reducing manpower and energy consumption and other parameters should be taken into account (Ghaffari, 1376). Machines for the shake-harvesting of tree fruits have been proposed for use in US fruits and nut crops since the early 1920s. Consequently various shakers have been developed to control the shaking motion of the trees and for the optimum harvest. These shakers developed to shake trunks of tart variety cherry trees at 10 to 24 Hz with 20 to 40 mm strokes, sweet cherry tree trunks at 12 to 24 Hz with 12 to 16 mm strokes for satisfactory fruit removal.

These frequencies are significantly above the first natural frequencies of a tart cherry tree (about 1 Hz) .

A common strategy used for harvesting the non-selective massive fruits are applying either impact forces or vibrational forces to induce a detachment force on fruits. During the shaking, a tree responds differently to different excitation frequencies. Vibratory fruit removal normally occurs when the detachment force exceeds the pedicel-fruit tensile force. Species bearing many small fruit per plant, such as sweet cherry and tart cherry are the best-suited for massive harvesting.

Many investigations of tree dynamics have been carried out based on the theoretical model analysis, see e.g., (Tsatsarelis, 1987; Upadhyaya et al., 1981; Whitney et al., 1990; Cooke et al., 1969) created a linearized, three degrees of freedom (3-DOF) model of a fruit-stem system to simulate the tree responses when subjected to a sinusoidal vibration. Tsatsarelis (1987) adopted the model of Cooke et al. (1969) to analyze the fruit removing actions for olive harvest. Upadhyaya et al. (1981) used a single degree of freedom model to describe the impact response of a tree. They found that only a certain amount of the exerted energy transmits to the tree. Whitney et al. (1990) modelled the tree trunk as a vertical cantilever and analyzed the dynamics of the shaker-tree system by including physical properties of both the tree and the shaker in their simulation.

The result of previous researches indicates that the magnitude of fruit detachment force depends on the amount of vibratory energy transmitted to the fruit spur and several physical properties including fruit physical characteristics such as volume, mass, length of stem, and degree of maturity), and tree morphological characteristics such as branch diameter, length, mass distribution, stiffness and damping coefficient.

An attempt to include the above mentioned parameters in the model was made by Whitney et al. (1990). The reduced mass, elasticity and the viscous damping coefficient were measured individually on a wooden post fixed to the ground as a vertical cantilever.

In a research performed by Diener (2008) found that shaking at the natural frequency is not effective for detachment of fruits from an apple tree, because the inertia forces in the apple stem are too small to cause separation. He proposed that higher frequencies of 400-600 cycles/min is necessary to remove Jonathan apples with a boom-type slider crank inertia shaker.

Due to the importance of physical and vibrational properties of trees for harvesting fruits in the shaking phenomena, an experimental investigation has been performed in this study for the apple, lemon and orange branches under different dynamic loads. The investigation is then followed by computation of their important vibrational properties, which could be used for the preliminary design of the shaking devices.

II. MATERIAL AND METHODS

To examine vibrational properties of the branches of horticultural products, tributaries of apple, lemon and orange trees were chosen from the research garden of Sari Agricultural and Natural Resources University to perform the experiments. End of each branch was fixed with a laboratory clamp and the initial vibrational conditions exerted on the other tip of the samples, i.e. 31-84 mm initial displacement by 0.56 N force. A ruler was mounted to the clamp very close to the tip of the samples, to measure the samples tip displacement during the vibration. Vibration of the samples were recorded by means of a digital video camera (Canon Sx

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120IS). With reviewing the recorded frames by BsPlayer software, displacement of the tip of the examined branches was measured and recorded. Given the frame rate of the captured movie equal to 30 frames per second (fps), several vibrational characteristics were computed and extracted from the frames, which will be discussed in the next section. Before conducting the measurements, physical properties of the samples such as branch length, diameter and weight were measured. Branch diameter was measured using a digital caliper with accuracy of 0.01 mm. The average branch diameter was obtained between 5.76 to 7.97 mm for apple, 4.23 to 4.85 for lemon, and 5.00 to 6.41 for orange samples, respectively. To obtain moisture content of the samples, branches were weighed before and after drying using a digital scale with an accuracy of 0.01 gr. For the moisture content measurement, some of the samples were dried with a laboratory oven at temperature of 103 ° C for 24 hr. Then the moisture content (MC) was computed using the following expression.

$$MC = \frac{m_w - m_d}{m_d} \quad (1)$$

where m_w and m_d stand for the wet mass and dry mass, respectively.

To start the vibrational experiments, samples were re-weighed to increase their moisture content equal to the harvest time, using the ASAE 2006 standard. The final moisture content of the samples reached to 45.6% for apple, 29.5% for lemon and 32.8% for orange branches (wet basis), which were equal to the moisture content at the harvest time.

Bending test was used to determine the stiffness factor of the branches. In this test, branch is simulated as a cantilever beam with a centralized mass at the end of it. The bending test was performed by using a tensile-pressure instron testing machine (model- STM 20 Santam) with a load cell of 2000 Kg and 0.001 N accuracy. Force and displacement data were recorded simultaneously on a computer. Elastic coefficient of branches, i.e., equivalent stiffness (K), was obtained through measuring the slop of the force-displacement data in the elastic range using the following relationship.

$$K = \frac{df}{dl} \quad (2)$$

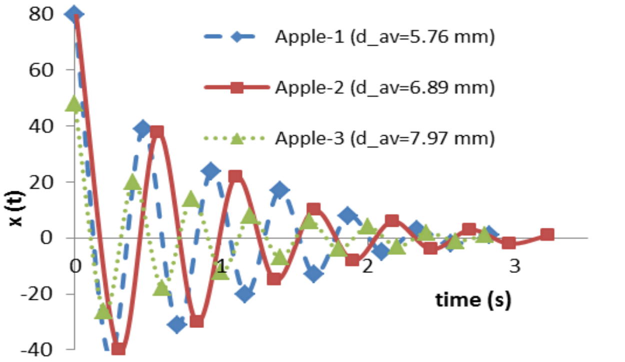
It should be noted that the numerical value of the spring factor (stiffness) for a cantilever beam is expressed in the form of

$$K = \frac{3EI}{l^3} \quad (3)$$

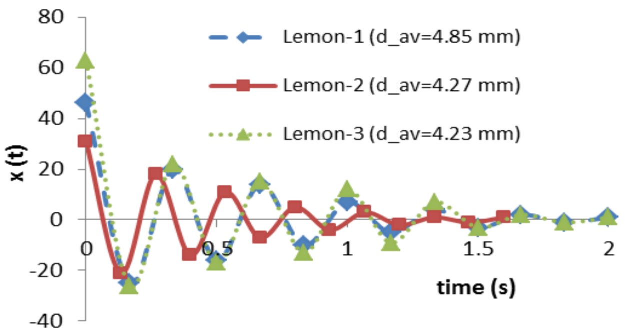
In this equation, E is modulus of elasticity MPa, I stands for the moment of inertia of the cross section of the branch mm^4 and L is the sample length *m*.

III. RESULTS AND DISCUSSIONS

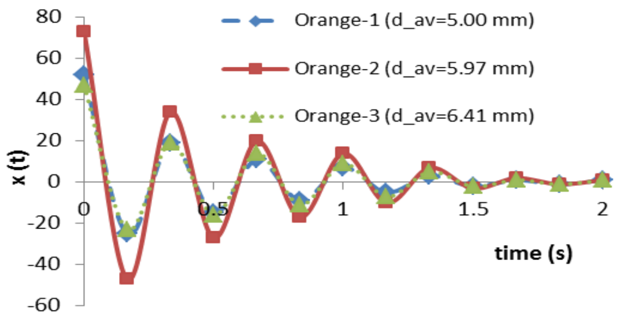
Given the results obtained from the captured video slides, displacement response of the examined branches versus time is plotted in Fig.1. According to the results shown in this figure, free vibration of the apple branches vanishes approximately after 3 sec, whereas the damping time for the lemon and orange branches were obtained equal to 1.8 sec .



a) Apple branches



b) Lemon branches



c) Orange branches

Fig 1 - amplitude of vibration of different branches versus time for the examined samples.

According to the results illustrated in Figs 1a, b, and c, the logarithmic decrement ratio of the amplitude is calculated using.

$$\delta = \frac{1}{m-1} Ln \frac{x_1}{x_m} \quad (4)$$

where x_1 is the first amplitude and x_m is the m(th) vibrating amplitude. After computing the logarithmic decrement ratio of the amplitude, damping ratio is calculated in the form of

$$\varepsilon = \frac{\delta}{\sqrt{\delta^2 + (2\pi)^2}} \quad (5)$$

The frequency of damped oscillation (ω_d) is calculated from

$$\omega_d = \frac{2\pi}{\tau_d} \quad (6)$$

where τ_d is periodicity of the damping oscillation. Then natural frequency of the branches was calculated using the following expression.

$$\omega_n = \frac{\omega_d}{\sqrt{1-\varepsilon^2}} \quad (7)$$

The spring factor (k), critical damping constant (c_c), and the damping coefficient (c) obtained by using the Eqs 8, 9 and 10, respectively [1-6].

$$k = m_{eq} . \omega_n{}^2 \quad (8)$$

$$c_c = 2m_{eq}\,\omega_n \quad (9)$$

$$c = \varepsilon c_c \quad (10)$$

The equivalent mass at the tip of the branch can be computed using the following expression.

$$m_{eq} = M + 0.23m \quad (11)$$

where m is mass of the branch and M is mass of the external weight at the tip of the branch, i.e., the fruit mass. Consequently the computed vibrational parameters are listed in Table 1 giving the expressions 3-10 for the three examined branches.

Table 1: Average computed vibrational properties of the apple, lemon and orange branches.

	Apple	Lomon	Orange
m_{eq} (Kg)	0.061	0.059	0.182
δ (mm)	0.463	0.438	0.461
ξ (No Unit)	0.073	0.069	0.073
τ_d (Sec)	0.47	0.30	0.33
ω_d (Sec^{-1})	13.64	21.19	18.84
ω_n (Sec^{-1})	13.68	21.25	18.89
C_c (Ns/mm)	1.68	2.51	6.87
K (N/mm)	11.68	27.03	64.87
C (Ns/mm)	0.12	0.17	0.50

Based on the investigations performed by Lorenzen et al. (1965), the approximate amount of damping ratio (ξ) for the horticultural branches is given equal to 0.1. According to the computed results given in Table 1, the average damping ratio of apple, lemon and orange branches are obtained equal to 0.073, 0.069 and 0.073, respectively. This is consistent with the results obtained by Lorenzen et al. (1965).

Variation of the vibrational amplitude with time for a 1D free vibration can be presented in the form of.

$$x(t) = e^{-\varepsilon\omega_n t}[x_0 \cos(\omega_d t + \varphi_0)] \quad (12)$$

where x_0 (initial amplitude) and φ_0 (initial phase difference) are constant parameters of the given relationship (12) which can be computed using the expressions 13-16.

$$x_0 = \sqrt{c_1'^2 + c_2'^2} \quad (13)$$

$$\varphi_0 = \text{Arc tan}\left(\frac{c_2'}{c_1'}\right) \quad (14)$$

$$c_1' = x_0 \quad (15)$$

$$c_2' = \frac{\dot{x}_0 + \varepsilon\omega_n x_0}{\omega_d} \quad (16)$$

Given the computed vibrational properties of apple, lemon and orange branches (listed in Table 1), and with the help of Eq. 12, variation of the vibrational amplitude of the apple, lemon, and orange branches can be simulated with 17, 18 and 19, respectively. These relationships can be re-considered in the initial design of the mechanical Shakers.

$$x(t) = e^{-0.99t}[70.88\cos(13.64t + 4.22)] \quad (17)$$

$$x(t) = e^{-1.46t}[47.11\cos(21.19t + 3.82)] \quad (18)$$

$$x(t) = e^{-1.38t}[57.50\cos(18.84t + 4.19)] \quad (19)$$

Comparison between the computed displacements using the model (Eqs 17, 18 and 19) and the experimental measurements are presented in Table 2. Comparing output of the model with the measurements indicates a good capability of the proposed model for the free vibration of the apple, lemon and orange branches.

Table 2: Comparison between the experimental measurements and the proposed model

T (Sec)		0.5	1	1.5	2
Apple	Experimental (mm)	42	24	16	7
	Model (mm)	42.4	25	14.6	8.3
Lemon	Experimental (mm)	20	9	4	1
	Model (mm)	21.9	9.9	4.3	1.7
Orange	Experimental (mm)	26	12	5	1
	Model (mm)	27.9	13.3	5.4	2.7

According to the results presented in Table 2, maximum error of the mathematical models for estimation of the vibrational amplitude after 1.5 sec are 8.75%, 6.80% and 7.4% for apple, lemon and orange branches, respectively.

IV. CONCLUSIONS

Given the results obtained in this study, the following conclusions can be summarized.

1. the apple, lemon and orange branches have approximately the same damping ratio (ξ) equal to 0.07.
2. the orange branches have a significantly larger stiffness constant (k) and critical damping constant (c_c) in compare to the apple and lemon branches.
3. the apple, lemon and orange branches have approximately the same damping ratio equal to 0.07, consistent with the results obtained by Lorenzen et al. (1965).
4. the proposed model has an acceptable accuracy for modelling the free vibration of the apple, lemon and orange branches.

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