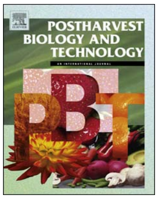
Postharvest Biology and Technology 138 (2018) 11–18

Contents lists available at ScienceDirect

Postharvest Biology and Technology

journal homepage: www.elsevier.com/locate/postharvbio



Nondestructive firmness measurement of differently shaped pears with a dual-frequency index based on acoustic vibration

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ARTICLE INFO

Keywords:
Firmness evaluation
Pear
Fruit shape
Frequency-based index
Piezoelectric transducers
Acoustic technique

ABSTRACT

An acoustic setup was developed to simultaneously detect the resonant frequencies f_1 from equator and f_2 from calyx shoulder of pear (*Pyrus bretschneideri* Rehd.). A proposed index based on these two frequencies was used for firmness evaluation of non-spherical pear. We confirmed the stability of this setup by repeatability analysis of acoustic response signal. When predicting the firmness of pears with large difference in fruit shape, the dual-frequency index was highly correlated with Magness-Taylor (MT) penetration firmness ($r = 0.951$). Compared with two types of single frequency-based indices, the firmness sensitivity of the dual-frequency index is mostly close to that of MT penetration test. The firmness index can classify pears with a high total accuracy (93.4%), making it suitable for nondestructive detection of firmness of differently shaped pears.

1. Introduction

Firmness is one of the reliable and universally accepted indicators for the internal quality evaluation of fruit, because it is closely related to their taste, ripeness degree, predicted shelf-life and mechanical bruise susceptibility. Traditionally, fruit firmness is measured by the Magness-Taylor (MT) penetration test, which uses a probe inserted into the tissue of a fruit at a certain speed to some depth to obtain slope of force-deformation curve in elastic stage and other correlative parameters. A texture analyzer or universe testing machine can also accurately determine fruit firmness. However, the methods are inherently destructive, time-consuming and labor-intensive (Arpaia et al., 2001). Therefore, it is incapable of meeting requirement of on-line detection for a massive number of fruit in industrial application.

Over the last decades, several non-destructive techniques have been the focus of the research in the field of fruit firmness detection, including near-infrared spectroscopy, hyperspectral image, nuclear magnetic resonance and ultrasonic methods (Butz et al., 2005; Ruiz-Altisent et al., 2010; Nicolaï et al., 2014). Although successful in laboratory trials, these techniques are not always suitable for low-cost and rapid implementation in commercial scale units. Hence, an inexpensive, rapid, and reliable method for fruit firmness measurement is highly desirable.

Non-destructive acoustic response techniques, applied with several types of sensors, can measure fruit firmness and are considered as a viable technology in quality assessment. Sensors to measure fruit vibration signals are classified into contact and non-contact types. Contactless transducer have been extensively adopted to obtain response signal, i.e. a microphone (Sugiyama et al., 1994; Steinmetz et al., 1996; Subedi and Walsh, 2009) or the laser Doppler vibrometer (LDV) (Terasaki et al., 2001; Oveisi et al., 2014; Zhang et al., 2014a,b, 2015). Although they are commercially useful, the microphone has limitations on the sensitivity to ambient environmental conditions like temperature, noise and air pressure (Abbaszadeh et al., 2015). A problem in applying LDV is cost-effectiveness due to the large size of the system and long excitation duration (Taniwaki and Sakurai, 2010). Thus, application of the contactless transducers is difficult in industrial scale. Contact sensor, i.e. an accelerometer, is directly glued to the fruit surfaces to detect the acoustic emission of fruit by applying impulse in early research (Finney, 1971, 1972; Abbott et al., 1992). By doing this, true tissue vibration can not be measured accurately because the additional mass loading interferes with flesh vibration of the tested sample (Muramatsu et al., 1997). The flexible piezoelectric transducer, which is a contact type of sensor, has drawn increasing attention recently because it overcomes the shortcomings of accelerometer. An interesting study reported by Macrelli et al. (2013a, 2013b) showed that small-sized piezoelectric transducers could precisely measure kiwifruit firmness. Hence, we also utilized this technique to detect the pear firmness (Wang et al., 2016a, 2016b). The results confirm that such approach is promising for industrial real-time and in-line applications.

For the non-destructive acoustic vibration tests, the resonance frequency f is predominantly used to characterize the firmness of fruit. The index f^2m, and later modified into $f^2m^{2/3}$ and $f^2m^{2/3}\rho^{1/3}$ (m being mass

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https://doi.org/10.1016/j.postharvbio.2017.12.002
Received 30 August 2017; Received in revised form 10 December 2017; Accepted 11 December 2017
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and ρ being density of the tested fruit), have been widely applied as the stiffness coefficient or firmness index of various fruit. These indicators have been reported as good firmness indices for sphere-shaped fruit, but they are not suitable for firmness evaluation of fruit with non-spherical or irregular shapes. Galili et al. (1998) introduced an additional frequency-related parameter, the centroid of the frequency response, for firmness evaluation of asymmetric avocado. Jancsók et al. (2001) developed an equation including the un-normalized resonant frequency and shape descriptor based on finite element modal analysis and used it to estimate the Young's modulus of differently shaped 'Conference' pears as a measure of its firmness. Cherng (2000) found that the frequency distribution of an ellipsoid was affected by the ratio of its principle axes. Cherng and Ouyang (2003) modified the conventional frequency-based index into a dual-frequency formula $(f_1 f_2^2)^{2/3} m^{2/3} \rho^{1/3}$ by theoretical derivation to estimate firmness of ellipsoidal melon. For the new index, f_1 and f_2 is the resonant frequency detected along major axis (equator of a fruit) and along minor axis (calyx or stem shoulder of a fruit) of fruit, respectively. Although this index is promising in predicting fruit firmness, they pointed out emphatically that it was only applicable to prolate ellipsoid. Given two resonant frequencies for solid ellipsoids, we also constructed an index $(0.6f_1 + 0.4f_2)^2 m^{2/3}$ by finite element modal (FE) analysis of differently shaped pears (Zhao et al., 2015). This dual-frequency index extends the firmness estimation for pears from a spherical to an ellipsoidal shape. Although the firmness index in relation to f_1 and f_2 for non-sphere shaped fruit has been theoretically developed, until now very few studies have carried out two point sensing techniques in the acoustic setup to test the feasibility of the new index.

Therefore, the objectives of this research were as follows: (i) to develop a piezoelectric transducer setup with two point sensing for firmness evaluation of pears; (ii) to investigate the correlation between the frequency-based firmness indices and MT penetration firmness of differently shaped pears, and (iii) to assess the ability of two point sensing setup for nondestructive firmness measurements of pears with our dual-frequency index.

2. Materials and methods

2.1. Firmness measurement with nondestructive acoustic method

2.1.1. Experimental setup

The detection system mainly consists of test bench, piezoelectric transducers (Q220-A4-303, Piezo Systems, USA), voltage amplifier (HA-405, Pintech, Taiwan), VibControl software to dynamically acquire signal and SO Analyzer 4.1 to analyze its results (m + p International VibControl, Germany), and a personal computer (Fig. 1). The setup uses three identical piezoelectric transducers: one operates as an actuator and two as sensors. Each transducer is composed of a $31.9 \times 12.7 \times 0.51\ \text{mm}^3$ cantilever beam consisting of two 0.19 mm thick piezoelectric ceramic layers and a center brass shim. The brackets installed with the transducers can be moved flexibly along the guide rail by hand. Until the middle part of cantilever beam contact the sample surface lightly, the bracket is fixed on the guide rail with the screw. To create a free support condition for the fruit, soft polyethylene-foam padding is selected as the fruit-bed (Galili et al., 1998).

2.1.2. Measurement of acoustic response signal

An original signal was recorded in advance by VibControl software for the acoustic vibration tests, which was produced by striking a force of 15 N on a pear with a rubber hammer (Xu et al., 2015). This signal was transformed into a positive half-sinusoid pulse V_E of 2.5 V (peak-amplitude) by SO Analyzer 4.1. Subsequently it was linearly amplified to a pulse excitation V_A of 80 V (peak-amplitude) by voltage amplifier HA-405, as presented in Fig. 2. The excitation V_A was outputted to the piezoelectric actuator in contact with the equator of pear sample and then propagated through the fruit. The responses V_R and $V_{R'}$ were detected by the piezoelectric transducers contacting the opposite side of equator and the calyx shoulder of the sample, respectively. Both the excitation V_A and the response V_R ($V_{R'}$) were acquired by the VibControl software with sampling rate of 51200 Hz for duration of 0.16 s and then analyzed using SO Analyzer 4.1. A pretrigger delay time was set to 5% in order to completely observe the transient signals. Some ripples of the response signal were filtered by Bessel low-pass filter with the cut-off frequency of 1600 Hz.

The typical frequency response spectra simultaneously sensing at equator and calyx shoulder of a pear were transformed from time-domain of response signals by a fast Fourier transform (FFT) algorithm, as shown in Fig. 3. Although some low-frequency noise can be observed due to vibrations from the mechanical supports of piezoelectric transducers, Macrelli et al. (2013a) pointed out that it did not alter identification of the resonance frequency. The respective resonant frequencies for two response spectra were then extracted.

2.1.3. Firmness index based on the resonant frequency

Our previous research (Zhao et al., 2015) showed that two resonant frequencies f_1 and f_2 can be measured easily at equator and calyx shoulder regions for an non-spherical pear, which are related to the first spherical mode and oblate-prolate mode respectively. Assuming that an ellipsoidal structure with these two vibration modes is equivalent to a spherical structure with certain constant resonant frequency f, so frequency f used in the conventional firmness index can be substituted by frequencies f_1 and f_2 with different weights. Therefore, according to the linear relationships of frequencies f_1 and f_2 with the fruit shape determined by our modal analysis of differently shaped pears, a newly dual-frequency firmness index can be expressed as:

$$S_{f_1,f_2} = (0.6f_1 + 0.4f_2)^2 m^{2/3} \tag{1}$$

where f_1 and f_2 are the resonant frequency acquired from equator and calyx shoulder regions of a fruit with two point frequency sensing setup, respectively.

The index proposed by Jancsók et al. (2001) is also used to measure the firmness of pears with different shapes as follows:

$$S_{E_1} = \frac{f_1^{\,2}(m/m_0)^{2/3}E_0}{(a_1 q + b_1)^2} \tag{2}$$

$$S_{E_2} = \frac{f_2^{\,2}(m/m_0)^{2/3}E_0}{(a_2 q + b_2)^2} \tag{3}$$

where m_0 and E_0, the constant properties used in the simulation, are 100 (g) and 5.84 (MPa), respectively; q is the shape descriptor defined as the average value of the maximum and the minimum of height divided by the average value of the maximum and the minimum of diameter for a pear (Zhao et al., 2015); a_1, a_2, $b_{1,}$ b_2 are constants depending on the mode shape. According our previous modal analysis for Korla pear (Zhao et al., 2015), the constants a_1, b_1 in Eq. (2) and a_2, b_2 in Eq. (3) are related to the first spherical mode and oblate-prolate mode, respectively. The values of these parameters were determined (Table 1).

In addition, since the two point sensing setup allows simultaneously acquiring f_1 and f_2, the conventional single frequency firmness index can be used as:

$$S_{f_1} = f_1^{\,2} m^{2/3} \tag{4}$$

$$S_{f_2} = f_2^{\,2} m^{2/3} \tag{5}$$

2.2. Firmness measurement with destructive method

Pear firmness was measured using the MT penetration test with a texture analyzer (TA.XT Plus, Stable Micro System, Britain). A cylindrical probe (5 mm in diameter) was steadily inserted into the flesh of an unpeeled pear to a depth of 8 mm at a speed of 1 mm/s. Twelve

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