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The use of a laser Doppler vibrometer to assess watermelon firmness

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ABSTRACT

Firmness is an important factor in describing the quality of agricultural products and is correlated with the vibrational characteristics of the object. In this study, the vibration response of 'Qilin' watermelons at postharvest was measured with an experimental system based on a laser Doppler vibrometer (LDV) for firmness detection. The vibration excitation applied by an electrodynamic shaker was monitored simultaneously with an accelerometer. After the excitation and response signals were transformed to the same dimension and converted from time-domain into frequency-domain by fast Fourier transform (FFT) processing, the ratio of response to excitation was calculated to determine the second resonance frequency (f_2). Subsequently, three widely used stiffness coefficients ($S_1 = f_2^2 m$, $S_2 = f_2^2 m^{2/3}\rho^{1/3}$ and $S_3 = f_2^2 m^{2/3}$, where m is the sample mass and ρ is the sample density) were calculated. These coefficients were selected as vibration parameters in addition to f_2. Moreover, a puncture test was conducted to obtain reliable firmness variables from force/deformation curves, including maximum force (F_{max}) and mean force at a 3–10 mm distance (F_{ave}). The effect of the measured locations of watermelons on f_2 was not significant, and a relatively stronger linear relationship was observed between S_2 and F_{max} ($r = 0.410$ with $P < 0.01$). However, no strong relations could be established between the vibration parameters and the firmness variables. This was most likely because of the firmness reference method, the watermelon variety or the small distributions of weight and density of the test samples. Further efforts are needed to identify the reasons for the weak relations.

1. Introduction

Firmness is an important texture attribute of food, particularly for fresh foods (Wang et al., 2006). Firmness provides information about the maturity, quality, shelf life and likelihood of possible physiological disorders (Galili et al., 1998; Molina-Delgado et al., 2009), which is very important for the grower, packer and retailer during the picking, grading, transporting, storing and distributing operations (Armstrong et al., 1990; Abbott and Liljedahl, 1994; Mirzaee et al., 2009).

Methods for measuring firmness can be destructive or nondestructive (Shmulevich, 1998). The most widely used destructive method for determining firmness is the puncture test, which measures the force required for a probe to penetrate into a sample to a specified depth (Lu, 2013). The main disadvantages of this method are that it fractures the object and that it cannot be repeated over time. Therefore, many nondestructive techniques have been developed for firmness assessment, such as vibration (Taniwaki and Sakurai, 2008), nuclear magnetic resonance (Marigheto et al., 2008), spectroscopy (Yancey et al., 2010), and spectral imaging (Huang and Lu, 2010). Of the nondestructive methods, the acoustic vibration techniques that measure the vibration characteristics of agricultural products to assess their firmness have received considerable attention (Terasaki et al., 2001; Symoneaux et al., 2005; Zude et al., 2006; Taniwaki and Sakurai, 2008).

In the measurements of vibration characteristics, determination of the resonant frequencies to acquire vibration characteristics has been suggested by many authors (Abbott et al., 1968; Cooke, 1972; Chen and De Baerdemaeker, 1993; Kondo et al., 2014) because resonant frequencies are related to elasticity, internal friction or damping, shape, size and density (Abbott, 1999). The general procedures for acquiring resonance frequencies are as follows: (1) impose a free vibration on the object by impact with a hammer or impose a forced vibration on the object with a vibrator, (2) record the vibration excitation and measure the vibration response of the object simultaneously, (3) transform the excitation and response signals to the same dimension and convert them from time-domain into frequency-domain by fast Fourier transform (FFT) processing, and (4) calculate the ratio of response to excitation to acquire the frequency response function and extract the

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dominant peak locations on the abscissa represented by the frequencies (resonance frequencies) denoted by f_n ($n = 1, 2, 3, \ldots$). Resonance frequencies may vary with object sizes. Therefore, to compensate for size differences, three stiffness coefficients (S_1, S_2 and S_3) incorporating the second resonant frequency, mass and density were proposed as firmness indicators (Abbott et al., 1968; Cooke, 1972):

$$S_1 = f_2^2 m \tag{1}$$

$$S_2 = f_2^2 m^{2/3} \rho^{1/3} \tag{2}$$

$$S_3 = f_2^2 m^{2/3} \tag{3}$$

where f_2 is the second resonant frequency, m is the sample mass and ρ is the sample density.

The sensors for measuring the vibration response of the object are classified as contact and noncontact types (Taniwaki and Sakurai, 2010; Kadowaki et al., 2012). The most frequently used contact senor was the accelerometer, which was directly attached to the surface of the object. Because the mass loading of the accelerometer could cause errors, particularly when testing light or small structures or highly damped nonlinear materials (D'Emilia et al., 1989; Castellini et al., 2006), true tissue vibration cannot be measured accurately with contact sensors (Terasaki et al., 2001). To overcome this drawback, alternative noncontact sensors, such as microphones (Mendoza et al., 2012; Costa et al., 2011) and the laser Doppler vibrometer (LDV), were introduced to provide a measurement of vibration response. The LDV measures the vibration velocity of the object via the Doppler shift of the laser beam frequency, which has a flatter response function over a wider range of frequencies compared with the microphone and shows superior performance over the microphone on its resistance to ambient noise (Taniwaki and Sakurai, 2010; Kondo et al., 2014). In the last few decades, detections of the firmness of agricultural products with the LDV have been extensively investigated. Muramatsu et al. (1997 and 1999) proposed that more accurate results for detecting the firmness of apples, kiwifruit, Japanese pears and Hassaku could be obtained with a LDV than an accelerometer and found that fruit firmness related not only with resonance frequency but also with the phase shift. Terasaki et al. (2001) applied this technique to monitor the changes in the viscoelastic properties of kiwifruit and found that S_3 decreased as kiwifruits ripened. Terasaki et al. (2006) employed the LDV to detect responses to imposed vibration of 'La France' pears and proposed a reciprocal model for simulating the decline in the value of S_3 during fruit ripening. The simulation showed that this model was appropriate for predicting the peak of ripeness for storage periods up to 2 months. Later, Taniwaki et al. (2009a,b) determined the period of optimum eating ripeness of pears, melons and persimmons by measuring the time course changes in S_3 with the same method. Recently, Abbaszadeh et al. (2013) developed a multivariate linear regression (MLR) model with the first and second resonant frequencies obtained with a LDV to predict the overall acceptability of watermelons; the model correlation coefficient was 0.82. They also used stepwise discriminant analysis (DA) to classify ripe and unripe watermelons and found 87.5% accuracy in the classification. Subsequently, the performance of the MLR model was improved with phase shifts at statistically selected frequencies, with a determination coefficient of 0.994 for the cross-validation model (Abbaszadeh et al., 2014).

In this study, a LDV system for vibration measurements was used to detect the firmness of 'Qilin' watermelons at postharvest. The objectives of this study were as follows: (1) determine the effect of measured locations of watermelons on the second resonant frequency, and (2) investigate the relationships among the vibration parameters (f_2, S_1, S_2 and S_3) of 'Qilin' watermelons and the firmness variables determined from force/deformation curves obtained with the puncture test.

2. Materials and methods

2.1. Samples

'Qilin' watermelon (*Citrullus lanatus*), a major variety cultivated in the south of China, were used in this study, which has juicy sweet flesh, nearly spherical shape and thin rind. Fifty-one watermelons were harvested in Hangzhou, Zhejiang province, China, of which 11 watermelons were used to investigate the effect of measured locations on the second resonant frequency. The other melons were kept in the laboratory at approximately 20 °C and 50% RH until the time for measurements, which resulted in storage durations ranging from 1 to 15 days. Five watermelons were randomly selected to measure the physical parameters, and the vibration measurements and puncture test were conducted every 2 days.

2.2. Physical parameter measurements

The mass (m) of a watermelon was recorded with an electronic balance (Max. 15,000 ± 1 g, DY15K, Jiangdong Precision & Scientific Instrument Co., Ltd., Jiangsu, China), whereas the volume (V) was measured using water displacement volumetry (Kaulesar Sukul et al., 1993). The density (ρ) of a watermelon equaled the m divided by the V. Moreover, caliper measurements (accuracy 0.01 mm) were taken for an accurate measurement of the height (H) and the equator diameter (D) of the watermelons.

2.3. Vibration measurements and vibration parameter calculations

The design of the vibration measurement system was similar to that used by Terasaki et al. (2001) (Fig. 1). The vibration measurement was applied at 4 locations on each watermelon, the stem end, the blossom end, the sun-exposed side and the shaded side (Fig. 2). For the location i (i = 1, 2, 3, 4), an intact watermelon with a reflective film at i for enhancing the laser reflection was mounted on an aluminum pedestal attached to an electrodynamic shaker (ES-05, Dongling Vibration Test Instrument Co., Ltd., Suzhou, China). A five to 1000 Hz sine wave swept for 110 s generated with a PC was fed to a power amplifier to drive the shaker. The vibration excitation applied with the shaker was monitored by an accelerometer (752A12, Meggitt's Endevco Corporation, California, USA) with a weight of 12.8 g and a flat frequency response from 0.5 Hz to 10 kHz. The vibration response of the watermelon was detected with a LDV (LV-S01, Sunny Instruments Singapore Pte., Ltd.,

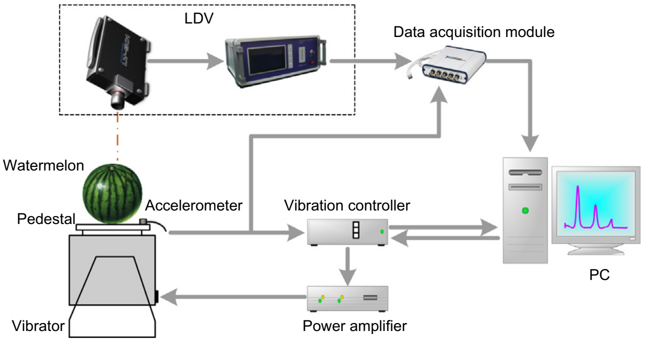

Fig. 1. System setup for measuring the vibrational spectrum from a location on a watermelon.