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Firmness evaluation of watermelon flesh by using surface elastic waves

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ABSTRACT

We measured the velocity of surface elastic waves on watermelon flesh for firmness evaluation. The Rayleigh waves at frequencies ranging from 800 to 2400 Hz propagate on the flesh and are detected by a piezo-bimorph sensor in contact with the flesh. We determined the shear elasticity from the velocity for two types of Japanese watermelons, Matsuribayashi777 and Wasenissho, to be 1.18 and 0.74 MPa, respectively. These correlated well with a sensory firmness evaluation. The values of Young modulus obtained by the surface-wave measurements were nine times larger than those by the compression tests performed, which can be explained by the differences in measurement displacement and frequency. We also investigated the effect of storage on the surface-wave velocity for Matsuribayashi777. The velocity decreased by about 10% after ten days of storage. The present results suggest that this technique can be applied to estimating the elastic properties of various fruits.

1. Introduction

There is an increasing need for better quality monitoring of watermelon. The major quality indices of watermelon are maturity, internal defects, and firmness/crispness. Various methods such as acoustic, electrical, magnetic, and X-ray techniques and near-infrared spectroscopy have been used to monitor these quality indices (Sun et al., 2010). In particular, the acoustic technique has been widely used. In the acoustic impulse response method for studying the natural frequency of watermelon with a pendulum hitting device, the sensory firmness or maturity is correlated with characteristic parameters composed of the resonant frequency of the detected sound waveform, and the mass and density of the watermelon sample (Clark, 1975; Yamamoto et al., 1981; Stone et al., 1994; Wang et al., 1999). Sugiyama et al. (1994) found that the velocity of an acoustic impulse decreased as melons ripened. A portable firmness tester, incorporating an impact plunger and two microphones, was also developed to measure the velocity, which correlates well with the apparent elasticity (Sugiyama et al., 1998).

Internal defects (voids or hollows) of watermelon can be investigated by the acoustic impulse response method. Diezma-Iglesias et al. (2004) showed that the low-frequency spectral-band (85–160 Hz) parameter was the best indicator of internal defects, which was confirmed by vibrational analysis using finite element simulation (Diezma-Iglesias et al., 2005). It has been pointed out, however, that the acoustic impulse signal is sensitive to the angle and location of the impact on the fruit surface. Furthermore, the elasticity modulus of external rind is larger than that of internal flesh by one order of magnitude (Sadrnia et al., 2008), which is a hindrance to determining the mechanical properties of the flesh.

Ultrasonic techniques have also been applied to the monitoring of quality indices of fruits and vegetables during various pre- and postharvest processes (Mizrach, 2008). Mizrach et al. (2000) developed a continuous-touch system for non-destructive evaluation of tissue characterization and quality indices of various fruits during the course of maturation, storage, and shelf life. In the through-transmission mode, the system consists of two ultrasonic transducers that are mounted in a structure that maintains a constant angle of 120° between the transducers' tips while in contact with a sample surface. The attenuation of ultrasonic waves with frequency of 50 kHz was found to change dramatically during storage, shelf-life, postharvest softening, and ripening of avocado, mango, and apple, whereas the change in ultrasonic velocity did not correlate with the physiochemical changes of the fruits (Mizrach et al., 1997, 1999; Kim et al., 2009).

We present here a new acoustic technique for the evaluation of the texture firmness of watermelon flesh. The technique was first developed by one of the authors for the estimation of elasticity in gelatin gels (Choi et al., 1999). Surface elastic waves at fixed frequencies ranging from 800 to 2400 Hz propagate on watermelon

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flesh. Detecting the propagation times of the surface waves at different positions gives the velocity, which, along with knowledge of the Poisson ratio, yields the shear elasticity of the flesh. Although the shear elasticity does not directly correspond to the sensory firmness, it provides a good representation of the firmness. Previous acoustic and ultrasonic techniques have not yielded the shear elasticity of fruits. In this paper, we examine two kinds of Japanese watermelons, namely Matsuribayashi777 and Wasenissho varieties, which in sensory tests have relatively hard and soft flesh, respectively. The Matsuribayashi777 variety has a crisper texture compared with Wasenissho. Compression tests were also made to obtain Young's moduli and Poisson ratios for the two varieties, and these results were compared with those determined by surface wave measurements.

2. Material and methods

2.1. Material

Two Japanese watermelon varieties, Matsuribayashi777 and Wasenissho, were supplied by Hagihara Farm Co., Ltd. (Nara, Japan). The surface wave measurements were carried out within five days after harvesting. Each watermelon sample was cut in half along its stem axis just before the measurement. All measurements were performed over four summer seasons from 2008 to 2012.

2.2. Surface elastic waves

Surface wave propagation in soft materials was theoretically considered by Onodera and Choi (1998), who showed that surface elastic waves (Rayleigh waves) could propagate on materials with small shear elasticity and surface tension. The velocity V of the surface elastic waves is given by

$$V = \frac{0.87 + 1.12\sigma}{1 + \sigma}\sqrt{\frac{G}{\rho}} \quad (1)$$

where G is the shear elasticity (rigidity), σ is the Poisson ratio, and ρ is the density. The theory was experimentally confirmed by Choi et al. (1999) in agarose gels. We can obtain the shear elasticity of watermelon flesh from the surface-wave velocity with knowledge of the Poisson ratio and the density by using Eq. (1).

Fig. 1 shows the experimental system we used for measuring surface waves in watermelon flesh. The surface elastic waves were excited by an oscillator (a metal bar with a length of 25 mm and diameter of 4 mm) connected to a shaker (Mini Shaker 4810, Bruel & Kjaer, Naerum, Denmark). The edge of the oscillator gently touched the cut surface of the watermelon flesh. A pulsed-wave signal with a duration of 20 cycles at 800–2400 Hz was applied to the oscillator by using a function generator (WF1944A, NF Corporation, Tokyo, Japan) and a power amplifier (PM4400, Marantz, Tokyo, Japan). We detected the pulsed waves using a piezo bimorph sensor (Fuji Ceramics, Shizuoka, Japan) with a size of $10 \times 10 \times 1$ mm^3. The signal was amplified and filtered with a preamplifier equipped with a band-pass filter (SR560, Stanford Research Systems, CA, USA), and was displayed on an oscilloscope (54616B, Hewlett Packard, CA, USA). At the beginning of the measurements, the distance between the oscillator and the bimorph sensor was set at approximately 5 mm. Signals were recorded with 2 mm increment of propagation distance by moving the sliding stage supporting the bimorph sensor. The time shifts of the detected peaks were plotted as a function of the propagation distance between the oscillator and the sensor, from which the surface wave velocities were obtained. The measured propagation distance was about 10 mm, and in this small region of the watermelon flesh we could determine the elastic properties. The accuracy of the velocity measurement is 4%, but the positional variation of velocity in a piece of watermelon is much larger. The measurements (Sections 2.2.1, 2.2.3, 2.2.4) were made near the center of a half-cut flesh where seeds were scarce. The measurements of dependence on sample thickness (Section 2.2.2) were made with cut-out samples.

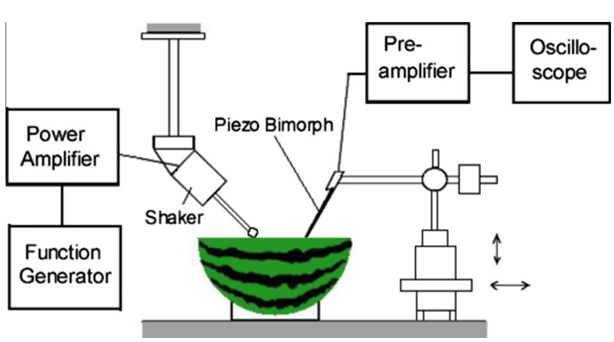

Fig. 1. An experimental system for measuring the surface-wave velocity on watermelon flesh.

2.2.1. Dependence of the surface-wave velocity on frequency

The frequency dependence of the surface-wave velocity was measured at 800, 1200, 1600, 2000, and 2400 Hz for the Matsuribayashi777 variety. The data sizes were 20–25 from samples of five watermelons for each frequency.

2.2.2. Dependence of the surface-wave velocity on sample thickness

Rayleigh-wave propagation assumes that the medium is an infinite half-space; this assumption may not be valid if the sample thickness is small. We measured the dependence of the surface-wave velocity on the sample thickness for the Matsuribayashi777 variety. The sizes of the flesh samples were almost 50 mm in width, 150 mm in length, and 5–90 mm in thickness. The flesh portions were taken from near the center of the fruit. The edge of the flesh sample was cut with a slope to prevent reflected waves. Wherever possible, seeds were not included in the samples to reduce their effect on the measurement.

2.2.3. Dependence of surface-wave velocity on watermelon variety

To investigate the difference in firmness between the two varieties, the surface-wave velocity was measured at frequencies of 800 and 2000 Hz for eight Matsuribayashi777 and four Wasenissho watermelons. The measurements were made near the center of the half-cut flesh where seeds were scarce. Four to ten data points were obtained for each watermelon, which were harvested during a different summer season from those used in the experiments of Sections 2.2.1 and 2.2.2.

2.2.4. Effects of storage on the surface-wave velocity

We examined the effects of storage time on the surface-wave velocity for Matsuribayashi777. The velocity was measured at frequencies of 800, 1200, 1600, 2000, and 2400 Hz two or three days after harvesting. The data size was 25 from five watermelons. The velocity was also measured 12 or 13 days after harvesting. In the latter case, the data size was 47 from ten watermelons. When stored, the samples were in a refrigerator at 5 °C.

2.3. Compression tests

We used compression tests to determine the Poisson ratio and Young's modulus of the two watermelon varieties. Fig. 2 shows the experimental system for measuring the Poisson ratio. After cutting a cubic sample (approximately $25 \times 25 \times 25$ mm^3) of flesh, we put it on the stepping-motor controlled three-dimensional sliding