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Evaluation of the Firmness Measurement of Fruit by Using a Non–contact Ultrasonic Technique

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In this study, we investigated the feasibility of using a novel non–contact ultrasonic technique to measure fruit firmness. The intensity of the reflected ultrasonic signal that bounces back from the fruit surface is dependent on the firmness of the fruit surface. However, differences in fruit size cause the reflected intensity to change with the distance separating the non–contact ultrasonic transducer and fruit surface. Therefore, it is necessary to eliminate the effect of fruit size on signal intensity to accurately predict fruit firmness when using a reflected ultrasonic signal. In this study, we developed and evaluated distance correction factors, which may reduce the size effects of fruit on the reflected ultrasonic signal. The distance correction factors were proposed using a combination of ultrasonic parameters obtained from the first and second reflected ultrasonic signals in the time and frequency domain. Fruit firmness parameters, such as bioyield strength and apparent elastic modulus, were measured and correlated with the distance corrected non–contact ultrasonic parameters. Multiple linear regression models to predict fruit firmness using ultrasonic parameters were assessed. The results demonstrated the potential utility of the distance corrected non–contact ultrasonic technique for the non–destructive measurement of fruit firmness.

Key words: fruit quality, firmness, non–contact ultrasonic, non–destructive measurement

INTRODUCTION

Recently, there has been an increasing preference for foods and agricultural products with quality and safety assurance guarantees. As a result, interest in developing techniques that evaluate the quality and safety of foods and agricultural products is steadily intensifying. This has led to the testing of various nondestructive quality evaluation techniques, such as near infra–red (NIR), nuclear magnetic resonance (NMR), sound, ultrasound, and machine vision. However, most of these techniques, except sonic and ultrasonic methods, are relatively expensive and unsuitable for the measurement of fruit firmness. This is because firmness is a mechanical phenomenon.

Acoustic methods have been successfully used to measure fruit firmness nondestructively, but they have some limitations for field application with a contact type ultrasonic technique. Kim *et al*. (2003) measured the mechanical properties and ultrasonic signal of apples with respect to storage times by using a contact type ultrasonic transducer. In another study, Hertog *et al*. (2004) studied the effects of humidity and temperature on the firmness of tomato and apple with contact ultrasonic measurements. The authors discriminated the effects of these environmental parameters on the biochemical process of cell wall breakdown and how this influences the physical process of water loss. The contact type ultrasonic transducer was used in a subsequent study by Kim *et al*. (2006) to measure the ultrasonic signal passing through the apple with respect to different storage times. The authors also analyzed the frequency components of the received ultrasonic signal by using wavelet transform. Next, Kim *et al*. (2007) successfully developed the 100 kHz and 200 kHz contact type ultrasonic transducers, which penetrate the whole fruit. Later, Kim *et al*. (2009) predicted the mechanical properties of the apple with respect to the storage times by using a contact type ultrasonic transducer developed by their research group.

Even though it is fast, accurate, and nondestructive, the measurement of fruit firmness by using the contact type ultrasonic transducer has a crucial limitation. To transmit the ultrasonic signal to sample fruit with minimal attenuation, a couplant (i.e., the medium used to facilitate the transmission of sound energy between the transducer and the test piece, such as ultrasonic gel, vacuum grease and water) must be placed between the transducer and the sample. The couplant improves the transmission efficiency of ultrasonic energy by matching the acoustic impedance between the transducer and the material. However, the couplant may contaminate and ruin the sample fruit. In addition, it is difficult to use the contacting method for the rapid and online measurement of individual fruit. The use of a non–contact ultrasonic technique might overcome the limitations of the contact ultrasonic measurement. The non–contact tech-

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nique does not require a couplant gel between the ultrasonic transducer and fruit; hence, it may serve as a useful nondestructive on–line sorting system for fruit.

In this study, the utility of the non–contact ultrasonic technique in measuring fruit firmness was investigated. Distance correction factors to compensate the distance between the non–contact ultrasonic transducer and the fruit surface caused by fruit size were calculated and applied to the model. This study also presents multiple linear regression models derived from the linear combination of the distance correction factors for predicting fruit firmness.

MATERIALS AND METHODS

SAMPLE PREPARATION

Apples ('Fuji') and peaches ('Hakuto') were purchased at a local market and used for the experiments. All samples were inspected to ensure that they were uniform, undamaged, and not infested with worms. After completing the inspection, the fruit samples were stored at room temperature (about 20°C) for up to 27 days to accelerate ripening. Subsequently, ultrasonic measurements of fruit firmness were conducted on random samples of 3 apples and 3 peaches. Force–deformation curves were obtained using a UTM to calculate the firmness properties of fruit, including bioyield strength and apparent elastic modulus. The loading rate of the crosshead for the firmness measurement was fixed at 5 mm/min, which was within the range of the loading rate specified by the American Society of Agricultural Engineers (ASAE) standard S368.3. The crosshead was a flat–bottomed cylinder that was 12 mm in diameter.

ULTRASONIC SYSTEM

The ultrasonic measurement setup consisted of a 500–kHz non–contact ultrasonic transducer, which was developed by our research group (Lee *et al.*, 2010), in addition to a pulser/receiver (DPR300, JSR Inc., USA), a digital oscilloscope (TDS5052D, Tektronix Inc, USA), and a jig for holding the ultrasonic transducer (Fig. 1).

The 2 centers of the non–contact ultrasonic transducer and a sample were placed along the same line. Then, the ultrasonic transducer was moved up and down along the line, to obtain the first reflected ultrasonic sig-

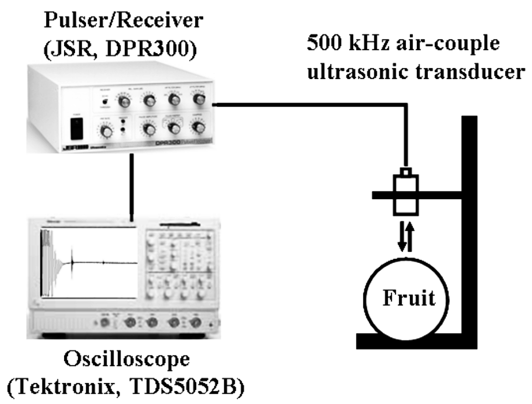


Fig. 1. Non–contact ultrasonic experimental setup.

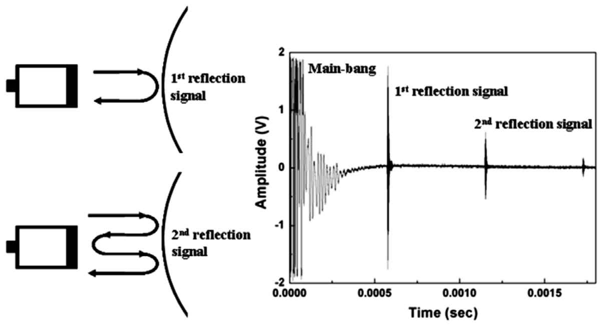
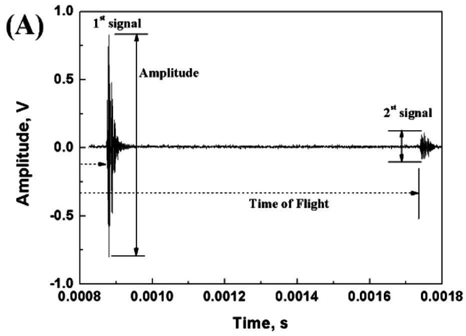
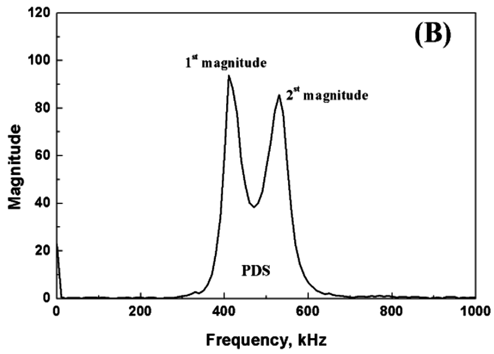


Fig. 2. Reflectance measurement of fruit surface by using a single non–contact ultrasonic transducer.



(a) Reflected ultrasonic signal



(b) FFT results of the first reflected ultrasonic signal

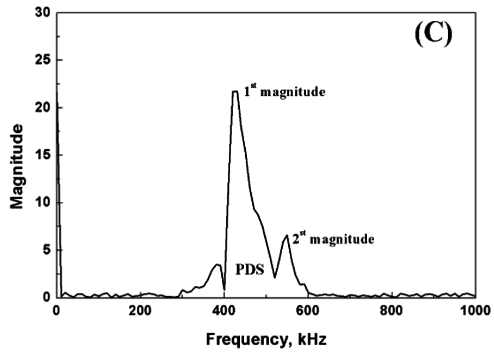


Fig. 3. Reflected ultrasonic signal of the time domain (a), FFT results of 500 kHz non–contact type ultrasonic transducer (b), and FFT results of the second reflected ultrasonic signal.

nal that was clearly separated from the main–bang signal. The sample position was also precisely rearranged to receive the maximum amplitude of the second reflected ultrasonic signal (Fig. 2). The received ultrasonic signals were stored on a portable memory card and analyzed using a personal computer. The measured ultrasonic reflected signals were analyzed in both the time domain and the frequency domain. In the time domain, the maximum amplitudes and the time–of–flight (TOF) of the reflected ultrasonic signals were obtained (Fig. 3a). In the frequency domain, the first and the second magnitudes and power spectrum densities (PSDs) of the reflected ultrasonic signals were obtained (Fig. 3b and 3c) by using the fast Fourier transform (FFT) algorithm.

DISTANCE CORRECTION FACTORS

The amplitude or energy of the reflected ultrasonic wave from the material with a flat surface is dependent on its coefficient of restitution when an ultrasonic wave is normally incident on the surface of an object. Since an ultrasonic wave is elastic, fruit firmness may be measured using the nature of the elastic wave. In other words, a firmer material surface generates an ultrasonic wave with greater amplitude, as long as the travel distance of the ultrasonic signal through the medium is constant. The ultrasonic intensity is highly attenuated while traveling through air at a constant rate of 163.7 dB/m (ISO, 1993). Hence, if the distance between the transducer and sample surface varies, the reflected ultrasonic intensity is highly influenced by the travel distance of the signal rather than surface firmness. When measuring the reflected ultrasonic signal from the fruit surface, the travel distance of the reflected signal is not constant because the distance between the non–contact ultrasonic transducer and the fruit surface changes according to fruit size. Hence, the amplitude of the reflected ultrasonic wave is altered by the external diameter of the fruit, rather than its firmness. The amplitude of the reflected ultrasonic signal is affected by the distance between the ultrasonic transducer and the fruit surface, as well as the external diameter. To accurately predict firmness by using the reflected ultrasonic signal, the effect of the travel distance of the ultrasonic signal should be eliminated from the reflected signal. This study proposes a novel concept of using the distance correction factors to remove the effect of variable travel distance from the reflected ultrasonic signal.

Under stable air medium conditions, the value of the ratio of the magnitude of the second reflected signal to the magnitude of the first reflected signal divided by the ratio of the TOF of the second reflected signal to the TOF of the first reflected signal is always constant, regardless of changes in the distance between the ultrasonic transducer and sample surface. Based on this assumption, 6 distance correction factors were empirically proposed by using the ultrasonic parameters of the first and the second reflected ultrasonic signals (such as TOFs, amplitudes, magnitudes, and PSDs) as follows:

$$Factor\_1 = (Amp\_2/Amp\_1)/(TOF\_2/TOF\_1) \quad (1)$$

$$Factor\_2 = (Mag\_21/Mag\_11)/(TOF\_2/TOF\_1) \quad (2)$$

$$Factor\_3 = (Mag\_22/Mag\_12)/(TOF\_2/TOF\_1) \quad (3)$$

$$Factor\_4 = (Mag\_12/Mag\_11)/(TOF\_2/TOF\_1) \quad (4)$$

$$Factor\_5 = (Mag\_22/Mag\_21)/(TOF\_2/TOF\_1) \quad (5)$$

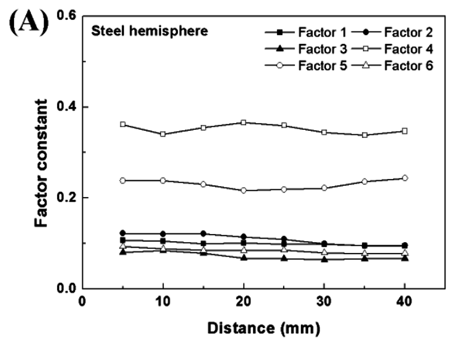
$$Factor\_6 = (PSD\_2/PSD\_1)/(TOF\_2/TOF\_1) \quad (6)$$

where, Amp_1 = the amplitude of the first reflection signal (V), Amp_2 = the amplitude of the second reflection signal (V), TOF_1 = the time of flight of the first reflection signal (s), TOF_2 = the time of flight of the second reflection signal (s), Mag_11 = the first magnitude of the first reflection signal, Mag_12 = the second magnitude of the first reflection signal, Mag_21 = the first magnitude of the second reflection signal, Mag_22 = the second magnitude of the second reflection signal, PSD_1 = the power spectrum density of the first reflection signal, and PSD_2 = the power spectrum density of the second reflection signal.

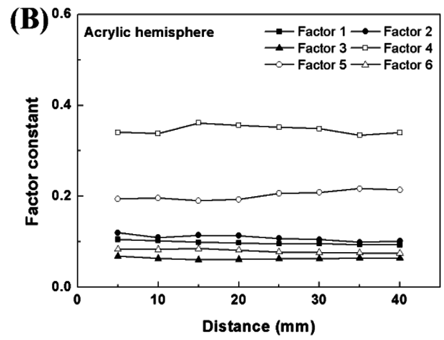
RESULTS AND DISCUSSIONS

EVALUATION OF THE DISTANCE CORRECTION FACTORS

If the distance between the ultrasonic transducer and sample surface is fixed, the attenuation of the ultrasonic



(a) Steel hemisphere

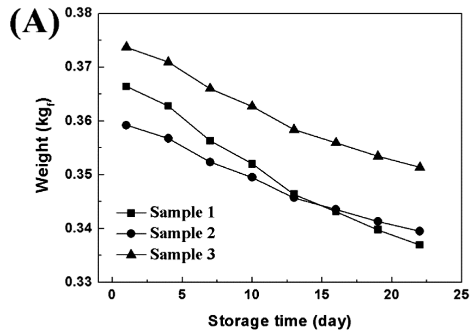


(b) Acrylic hemisphere

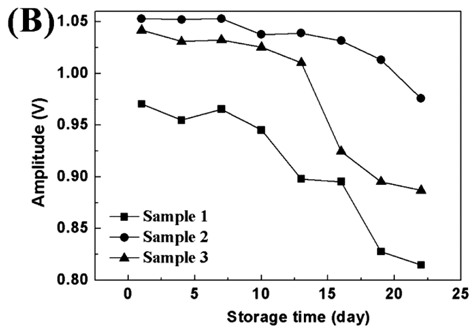
Fig. 4. The calculated results of distance correction factors for different distances between the ultrasonic transducer and the surface of steel (a) and acrylic (b) hemispheres.

wave, which occurs in air, always has a regular value. At this point, the ratio of the first reflected ultrasonic signal to the second reflected ultrasonic signal from the sample surface simply depends on the difference of the sample surface firmness. While the distance between the ultrasonic transducer and the sample surface is altered, the distance correction factors proposed in the previous section may not be altered. To evaluate the invariance of the proposed distance correction factors with changing distance between the transducer and the sample surface, steel and acrylic hemispheres that were 100 mm in diameter were used.

The ultrasonic signals reflected from the surfaces of the steel and the acrylic hemispheres were measured as the position of the ultrasonic transducer increased from 5 mm to 40 mm at intervals of 5 mm, and then the distance correction factors were calculated. The calculated values of the factors were nearly uniform, without any tendency to increase or decrease, when the distance was changed from 5 mm to 40 mm, as shown in Fig. 4a and 4b. The results indicated that the calculated distance correction factors mostly supported the assumption. The slight change in the values might be caused by a small change in air property, such as temperature, humidity, or air flow, during the measurements.



(a) Weight change



(b) Amplitude change

Fig. 5. Changes in the weight (a) and reflected ultrasonic intensity (b) for different apple storage times.

CHANGES IN REFLECTED ULTRASONIC SIGNALS AND FIRMNESS VALUES ACCORDING TO STORAGE TIME

To identify the correlation between the reflected ultrasonic signal on the fruit surface and fruit firmness, the change in amplitude of the first reflected ultrasonic signal and the weight loss of the apple were measured in relation to storage time. As a result of this pilot experiment, the weight of the apple linearly decreased with increasing storage time (Fig. 5a). However, the amplitude of the first reflected ultrasonic signal from the apple surface gradually decreased until about 10 days, after which it steeply decreased, as shown in Fig. 5b. This phenomenon is attributed to the effect of a time delay on the internal change of the apple rind, while the drop in apple weight is due to the weakening of its density and firmness by biochemical reactions, such as hydrolysis and aerobic respiration. Fruit weight loss is directly related to the stiffness or firmness of the rind and pulp (Hertog *et al.*, 2004).

FRUIT FIRMNESS PREDICTION MODELS

Multiple linear regression models were developed using distance correction factors to predict the bioyield strength and the apparent elastic modulus of apples and peaches. Tables 1 and 2 show the multiple linear regression models and coefficients of determination of bioyield strength. Tables 3 and 4 show the apparent elastic modulus at 3 different measurement distances (5 mm, 10 mm, and 15 mm) between the transducer and fruit samples. The coefficients of determination in the prediction models for bioyield strength exceeded 0.82. The coefficients of determination in the prediction models for the apparent elastic modulus were below 0.8, with the overall values being lower than those obtained for bioyield strength. Although the coefficients of determination for the firmness prediction of apples were not significantly different, the coefficients for peach were noticeably high at a dis-

Table 1. Multiple linear regression models for the bioyield strength of apples

Apple	BS = a×Factor_1+b×Factor_2+c×Factor_3+d×Factor_4+e×Factor_5+f×Factor_6+g							R^2	Standard error
	a	b	c	d	e	f	g		
5 mm	1657.57	–3359.66	3039.79	1242.53	–663.54	–444.79	–169.97	0.824	13.48
10 mm	1720.27	–3499.75	3251.95	772.69	–891.96	–992.93	180.72	0.831	13.15
15 mm	1089.65	–937.37	208.23	–28.93	8.21	–889.28	250.83	0.838	10.37

Table 2. Multiple linear regression models for the bioyield strength of peaches

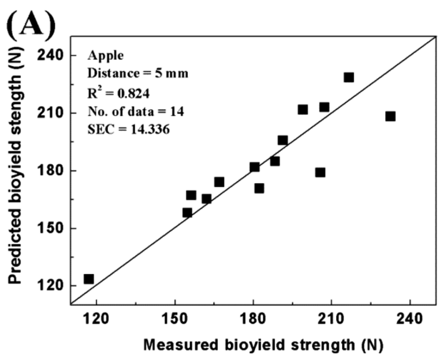
Peach	BS = a×Factor_1+b×Factor_2+c×Factor_3+d×Factor_4+e×Factor_5+f×Factor_6+g							R^2	Standard error
	a	b	c	d	e	f	g		
5 mm	112.72	32.86	–253.73	–93.66	68.11	68.11	39.72	0.922	3.45
10 mm	196.59	–336.36	147.82	–25.62	3.68	–66.68	40.35	0.823	5.00
15 mm	39.95	–43.88	88.59	–62.16	68.34	68.11	1.64	0.843	5.15

Table 3. Multiple linear regression models for the apparent elastic modulus of apples

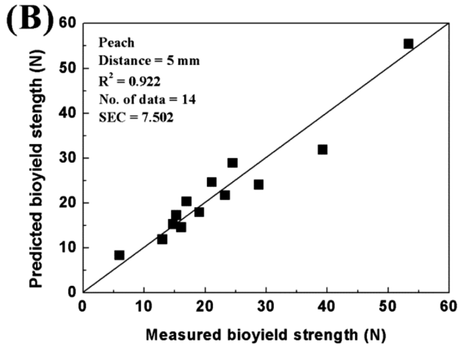
Apple	EM = a×Factor_1+b×Factor_2+c×Factor_3+d×Factor_4+e×Factor_5+f×Factor_6+g							R^2	Standard error
	a	b	c	d	e	f	g		
5 mm	–21227.41	24674.12	–7604.37	–3556.17	7484.05	–15186.17	4128.13	0.685	290.12
10 mm	–4641.52	–15861.70	48266.52	5104.66	–8933.84	–22937.46	4515.34	0.532	557.44
15 mm	19692.71	–20609.59	41286.97	6813.57	–8005.80	–22407.31	2272.86	0.706	195.77

Table 4. Multiple linear regression models for the apparent elastic modulus of peaches

Peach	EM = a×Factor_1+b×Factor_2+c×Factor_3+d×Factor_4+e×Factor_5+f×Factor_6+g							R^2	Standard error
	a	b	c	d	e	f	g		
5 mm	738.10	185.18	–2549.49	–1013.56	713.23	1271.62	435.21	0.797	61.62
10 mm	734.39	–926.79	48.54	–621.66	416.51	–276.40	414.66	0.688	49.53
15 mm	3904.10	–11041.09	10308.07	718.93	–846.46	799.01	–132.66	0.512	80.26

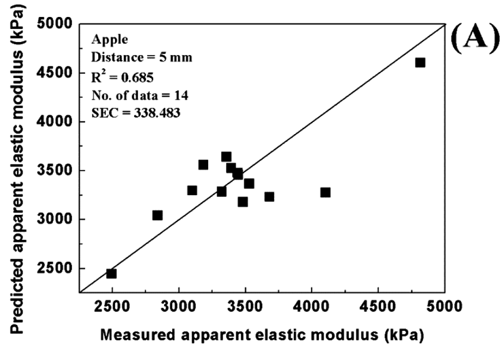


(a) Apple

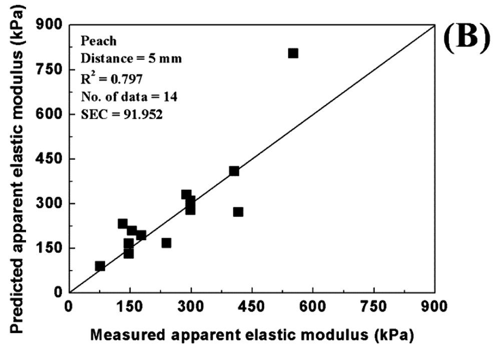


(b) Peach

Fig. 6. The relationship between the measured and predicted bioyield strengths when the surfaces of (a) apples and (b) peaches are placed at 5 mm distance from an ultrasonic transducer.



(a) Apple



(b) Peach

Fig. 7. The relationship between the measured and predicted elastic modulus when the surfaces of (a) apples and (b) peaches are placed at 5 mm distance from an ultrasonic transducer.

tance of 5 mm. This variation may arise because the shorter measurement distance may have had a lower influence on changes in air property during the measurements. The measured and predicted bioyield strength and apparent elastic modulus of apples and peaches are presented in Figs. 6 and 7. The results demonstrate the apparent tendencies of the linear relationship between the actual and predicted values. This study confirms that it is possible to measure fruit firmness by using the non–contact ultrasonic technique; however, the external diameter of fruit was altered to some degree. Additional research may be necessary to verify the exact performance of distance correction factors under a variety of experimental conditions, such as sufficient sample quantity, various cultivars, and wide firmness ranges.

CONCLUSIONS

In this study, we investigated the feasibility of predicting fruit firmness by using a non–contact reflectance ultrasonic technique. This technique is advantageous in that it uses a single transducer, which makes the measurement simple, low–cost, rapid, non–destructive, and operational in an on–line setup. The main drawback of the technique is the high sensitivity of the signal intensity to changes in the distance between the ultrasonic transducer and the sample surface. The performance of the 6 distance correction factors that were proposed to eliminate the effects of changing distance was evaluated. Even though the distance between the ultrasonic transducer and the fruit surface varied with the size of each individual fruit, the 6 distance correction factors minimized the distance effects of the reflected ultrasonic signals, allowing the accurate prediction of fruit firmness. Multiple linear regression models were developed using the distance correction factors for predicting apple and peach firmness. The coefficients of determination in the models for predicting bioyield strength exceeded 0.82 for both apples and peaches. The study results demonstrated that non–contact ultrasonic measurement by using a single transducer may be potentially used for the non–contact and rapid determination of apple and peach firmness.

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