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The impulse response method for pear quality evaluation using a laser Doppler vibrometer

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ABSTRACT

The impulse response method using a laser Doppler vibrometer (LDV) was performed to nondestructively measure pear quality. To get a wide range of texture and different freshness in pears, the experiment was conducted every other day during 7 days storage. Each pear was excited by a half-sine impulse signal, and an LDV was used to measure the response signal from the top of the pear. A fast Fourier transform algorithm was used to transform time domain signals to frequency domain signals. A total of 15 and 8 features were extracted from the time and frequency domain signals, respectively. Pear texture was measured by the puncture test. Maximum force (*MF*), flesh firmness (*FF*) and stiffness (*Stif*) were extracted from the force–deformation curve as texture indices. Different modeling methods, including the stepwise multiple linear regression (SMLR), back propagation neural network (BPNN), and principal component analysis-back propagation neural network (PCA-BPNN) methods, were used for quantitative analysis of pear texture. Best prediction results were obtained by the PCA-BPNN method, especially for predicting *FF* with correlation coefficient (r_p) of 0.840 and root mean square error of prediction (RMSEP) of 0.959 N. The Fisher's discriminant analysis (FDA), BPNN, and PCA-BPNN methods were applied to qualitative analysis of pear freshness. Pears were categorized into 4 groups with different freshness according to the 4 test days. The best results were also obtained by the PCA-BPNN method, resulting in accuracy of 89.0% and 83.3% for calibration and validation, respectively. Experimental results showed that the impulse response method using an LDV is capable for evaluating pear texture and freshness. The proposed approach provides a way for rapid detection of pear quality to meet the requirement of on-line detection.

1. Introduction

Texture is one of the key quality attributes used in the fresh and processed food industry to evaluate the quality and acceptability of food product (Chen and Opara, 2013). Various approaches have been proposed for nondestructive measurement of fruit texture. Among the existing detection techniques, the acoustic vibration method is an effective and commonly used method for fruit texture evaluation (Taniwaki and Sakurai, 2010b).

The laser Doppler vibrometer (LDV), as a remote sensing technology for vibration measurement, has advantages of high spatial resolution with reduced testing time, fast dynamic response, and increased performance compared with traditional vibration sensors (such as accelerometers and strain gauges) (Castellini et al., 2006). LDV has been applied in various occasions, including mechanical engineering, smart materials, civil engineering, biomedical applications, agriculture, etc. (Castellini et al., 2006; Santulli and Jeronimidis, 2006). Muramatsu et al. (1997) first introduced the LDV into nondestructive measurement of agro-product quality.

Acoustic vibration methods are classified into impact methods and forced vibration methods according to the mechanical excitation method (Taniwaki and Sakurai, 2010b). In most studies about the LDV method for nondestructive measurement of agro-product quality, samples were usually excited by the forced vibration method. The electrodynamic vibrator provided a varying force for the tested sample, and an LDV was used to measure the response signal. The excitation signal to the vibrator was usually a gradually increasing or decreasing frequency within a certain frequency range. The excitations were further classified into random and swept sine wave excitations (Taniwaki and Sakurai, 2010b).

Muramatsu et al. (1997) applied a swept sine wave signal (frequency, 5–2000 Hz) to fruit, and detected the response signal by an LDV and an accelerometer separately. They found the resonance frequency and phase shift measured by the LDV method were more

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sensitive and precise. Later, Muramatsu et al. (1999a,b) used the same excitation signal for kiwifruit, apple, persimmon, peach, and citrus. Results showed that the LDV method was capable for fruit firmness evaluation and citrus internal disorder detection. Terasaki et al. (2001, 2006, 2013) applied a swept sine wave signal (frequency, 20–3000 Hz) to kiwifruit and pears. They concluded that the LDV method can be used to monitor fruit ripening behavior and detect fruit texture. Taniwaki et al. (2009c; 2010a) adopt a swept sine wave signal (frequency 0–1000 Hz) to melons, and measure the vibration response by an LDV. They proved that it was feasible to determine the ripening speed and optimum speed of melons through the elasticity index. In addition, the swept sine wave signal (frequency, 0–2000 Hz) was applied to persimmons and pears by Taniwaki et al. (2009a,b). Results showed that fruit texture measurement and the prediction of optimum eating ripeness by the LDV method were feasible. Abbaszadeh et al. (2011, 2013, 2014) used random wave signals (frequency, 0–1000 Hz) in the LDV method for evaluation of watermelons texture, and demonstrated this method for predicting watermelon texture was feasible. Zhang et al. (2014a,b) applied a swept sine wave signal (frequency, 100–2000 Hz) to pear texture measurement by the LDV method. Results showed that pear texture measurement by the proposed method was feasible, and the performance of the prediction model was improved after the introduction of fruit shape index.

The method using swept sine wave excitation has the advantage of accurate measurement of resonance frequency, because it enables the excitation energy to be concentrated in a small frequency band at a specific moment (Taniwaki et al., 2010a; Taniwaki and Sakurai, 2010b). However, the method using swept sine wave excitation is time-consuming and not suitable for online detection. The impulse excitation is fast because the excitation energy spread over a wide frequency range in a short time (Taniwaki et al., 2010a). Few researches have studied the LDV method with impulse excitation for nondestructive measurement of agro-products quality. Therefore, the impulse excitation was used in the LDV method for pear quality evaluation in this study.

The objectives of this study were to investigate the feasibility of the LDV method with impulse excitation for (i) quantitative analysis of the pear texture and (ii) qualitative analysis of pears with different freshness.

2. Materials and methods

2.1. Pear samples

Pears (*Pyrus pyrifolia* cv. 'Hosui') were hand harvested at their optimum harvesting time (August, 2014) at the orchard of Sanshui Fruit Co., Ltd., Hangzhou, China. First, 15 pear samples were used for a test to evaluate possible mechanical damage to fruit due to the impulse by the vibration stage. The remained samples were stored in a refrigerating chamber with a temperature of 4 °C. After the possible damage evaluation, a total of 125 pear samples (Table 1), after 2 weeks storage at 4 °C, were transferred to the laboratory in controlled temperature condition at about 23 °C. These samples were used to measure their impulse response by an LDV and to detect texture by the puncture test.

Table 1
Morphological properties of the tested pear samples ($n = 125$).

	Mass (m, g)	Diameter[a] (d, mm)	Height[a] (h, mm)	Shape index[b] (SI)
Mean	313.65	86.15	72.61	0.84
Maximum	417.33	94.64	83.74	0.97
Minimum	246.85	79.01	65.26	0.78
Standard deviation	33.37	3.20	3.32	0.03

[a] Mean value of three measurements taken at an interval of 120°.
[b] Shape index: the ration of height to diameter (h/d).

2.2. Measurement of impulse response of pears

The system for measuring impulse response of pears was the same as that used in our previous study (Zhang et al., 2014b). The difference is that the impulse signal was chosen as the excitation signal instead of the swept sine wave signal in this study. The pear was placed on the middle of the vibration stage of the vibrator (ES-05, Dongling Vibration Test Instrument Co., Ltd., Suzhou, China) with stem upward and excited by a half-sine impulse signal with impulse amplitude of 2 g ($g = 9.8$ m/s^2). The impulse signal applied to the vibrator was first generated by a PC, and then amplified by a power amplifier (PA-1200, Dongling Vibration Test Instrument Co., Ltd., Suzhou, China). An LDV (LV-S01; Sunny Instruments Singapore Pte., Ltd., Singapore) was used to measure the response signal from the top of the pear. The data sampling frequency was 5120 Hz. As shown in Fig. 1(b), the extraction of response signal starts when the amplitude of collected signal is greater than 1 mm/s and ends when it is smaller than 1 mm/s by an intelligence algorithm. Fig. 1(a) and (b) shows a typical half-sine

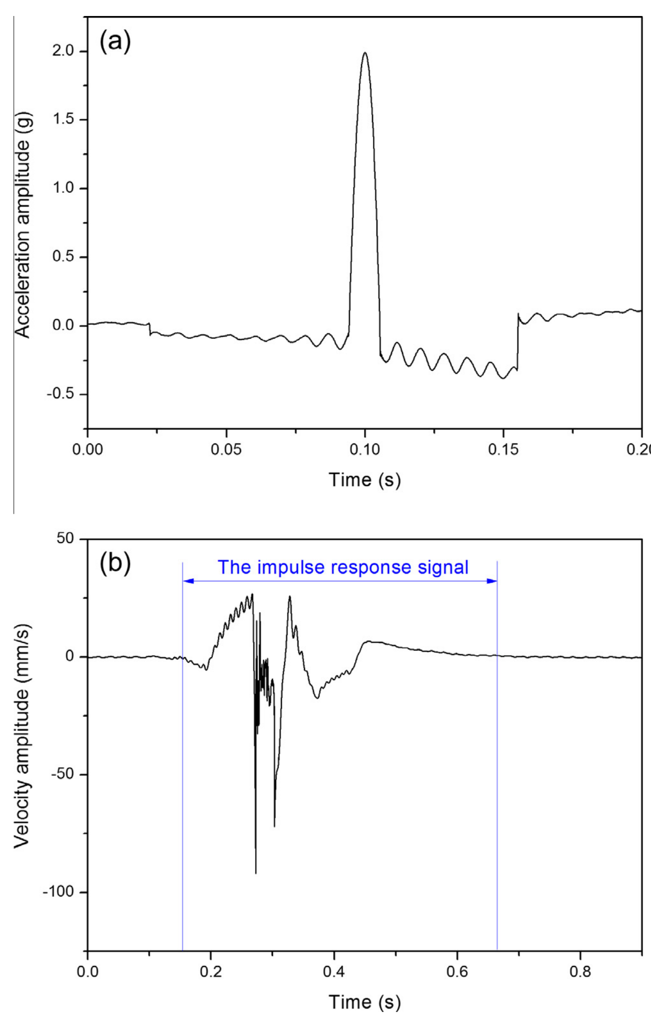

Fig. 1. A typical half-sine pulse signal for pears (a) and a typical response signal measured by a laser Doppler vibrometer (LDV) from the top of the pear (b) ($g = 9.8$ m/s^2). The extraction of response signal starts when the amplitude of collected signal is greater than 1 mm/s and ends when it is smaller than 1 mm/s.