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Application of infrared lock-in thermography for the quantitative evaluation of bruises on pears

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HIGHLIGHTS

- An infrared lock-in thermography was used for the detection of early bruise on pears.
- A photothermal wave model was employed to investigate the behavior of that on a pear.
- Damaged area causes thermal wave delay.
- A greater phase difference corresponds to greater damage to the pear.

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ABSTRACT

An infrared lock-in thermography technique was adjusted for the detection of early bruises on pears. This mechanical damage is usually difficult to detect in the early stage after harvested using conventional visual sorting or CCD sensor-based imaging processing methods. We measured the thermal emission signals from pears using a highly sensitive mid-infrared thermal camera. These images were post-processed using a lock-in method that utilized the periodic thermal energy input to the pear. By applying the lock-in method to infrared thermography, the detection sensitivity and signal to noise ratio were enhanced because of the phase-sensitive narrow-band filtering effect. It was also found that the phase information of thermal emission from pears provides good metrics with which to identify quantitative information about both damage size and damage depth for pears. Additionally, a photothermal model was implemented to investigate the behavior of thermal waves on pears under convective conditions. Theoretical results were compared to experimental results. These results suggested that the proposed lock-in thermography technique and resultant phase information can be used to detect mechanical damage to fruit, especially in the early stage of bruising.

1. Introduction

As international competition in agricultural markets has intensified owing to the proliferation of free trade agreements between countries, many changes have occurred in the agricultural industry. In particular, quality evaluation of agricultural products has been considered a significant part of quality control during the post-harvest process. As a result, the detection of mechanical defects is an important consideration in quality inspection systems for fruits. Existing automatic sorting systems are insufficiently precise when detecting bruises, especially early bruises. In spite of the fact that bruising is the main reason for rejection when sorting, the manual sorting method is still used [1]. Bruising is defined as damage to the fruit tissue as a result of external forces, causing physical changes in texture and chemical changes in color, smell, and taste [2]. Two basic effects of fruit bruising can be distinguished, i.e., browning and softening of fruit tissue. However, the majority of bruise detection methods currently used show deficiencies for dark-colored fruits or small-area bruises. It has also been observed that the susceptibility of apples to mechanical damage depends on many factors including soil cultivation, nutrition, and weather conditions in the field during growth [3].

Thus, extensive research into the nondestructive quality evaluation of agricultural products (such as vegetables and fruit) in the postharvest process has been undertaken by the agricultural industry. Recently, nondestructive optical techniques have been proposed as an alternative to the conventional methods for detecting mechanical damage to fruits. The application of the near infrared spectroscopy method (NIR 700–2200 nm) has shown limited effectiveness for bruise detection in the case of multicolored apples, e.g., 'Jonagold' or 'Braeburn', and for early bruising [4–7].

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In addition, various nondestructive measurement methods with enhanced analysis techniques such as ultrasound [8–10], X-ray imaging [11–13], and electromagnetic and magnetic resonance techniques [14–18] have been developed to evaluate the internal quality of fruit and vegetables.

In addition to the above technologies, new applications of infrared thermography to the evaluation of agricultural products and bio-related materials have been explored because this technique is useful not only for measuring the temperature on the surfaces of objects but also for detecting subsurface or internal heat intrusions and the heterogeneity of the thermal properties within objects, which might serve as sensitive indicators of cell viability in living organisms [19–21]. It has been shown that defects in agricultural products manifest themselves as changes in the thermodynamic properties of the affected tissue [22,23]. Researchers have indicated that infrared thermography can bring new possibilities to apple bruise detection, provided that the process of heat conduction in the fruit can be precisely identified and the mechanism of heat contrast creation between the bruised part and sound areas on the fruit's surface is understood [24,25].

Although infrared thermography techniques have many merits, such as nondestructive, non-contact, and allow for full-field imaging and fast inspection speed, they also have some limitations caused by the measurement sensitivity. However, the limitations of infrared thermography have been gradually overcome by combining several technologies and control systems that are supported by computerized image processing techniques. The detection and classification of defects using infrared thermography has significantly increased in performance as a result of these combined technologies such as lock-in techniques. Thus, lock-in technique has been applied to infrared thermography to enhance its detection sensitivity [26–29]. The idea of this phase sensitive modulated thermography technique was first presented by using the AGEMA Thermovision 900 mirror scanner thermocamera which was the infrared camera with lock-in function [26]. The noise equivalent temperature difference of the system was evaluated as 15 mK, and it was not significant improvements over previous techniques. After that, dynamic precision contact thermography was developed as the first lock-in thermography technique which able to detect temperature below 100 μK with a spatial resolution of approximately 30 μm [27]. However, this contact method showed limitations in the nondestructive evaluation of materials or integrated circuits. Since the late 1990 years, a highly sensitive infrared lock-in thermography system has been developed, and used in the several industries such as electronics, aircraft, and defense for the nondestructive thermo-mechanical investigations. This technique uses periodic excitation methods using thermal, vibration, or ultrasound waves; the resulting amplitude and phase information represents an indication of damage including both the size and the depth of the damage. Wu and Busse [28] described the principle of lock-in thermography and demonstrated that lock-in thermography can eliminate disturbances such as surrounding reflections, local variations of the surface optical absorption and the infrared emission coefficient, and inhomogeneous illumination by heating sources. Choi et al. [30] evaluated the sizes and locations of subsurface defects using lock-in infrared thermography and showed that a phase difference between the defect area and the healthy area indicates the qualitative location and size of the defect.

In this study, we constructed an infrared thermal system consisting of a mid-IR range (1.5–5 μm) infrared camera and halogen lamps. We then analyzed the infrared thermal signals to identify the damage area and depth on pears using a lock-in thermography technique. In this method, a periodic rectangular heat pulse was generated by halogen lamps, and the characteristic thermal response of objects was analyzed on the basis of phase images. In addition, a photothermal model of periodic thermal waves under convection conditions was implemented to analyze the behavior of thermal waves from pears in which defects existed. The model was then used to predict the result of inspection. Experimental results were compared to verify the photothermal model and determine the performance of lock-in thermography. This quantitative estimation of damage on pears was performed using the phase difference between the damaged area and the intact area of each pear.

2. Materials

Pears (Korean Niitaka cultivar) harvested in October 2012 were used, and test samples were selected to match their equivalent graded products. The pears were sorted according to size, weight, and color using a conventional sorting machine and humans in an agricultural products processing center. Selected pear samples were visually inspected to ensure that they were uniform, undamaged, and not infested by worms. After completing the naked-eye inspection, all pear samples were stored at a controlled temperature of 4 °C and a relative humidity of 80% RH. In addition, pear samples were stored at room temperature of 20 °C and a relative humidity of 70% RH for five hours shortly before applying compressive forces and obtaining infrared thermal images. Pear samples were artificially damaged by compressive force using a universal testing machine (UTM, Sunyoung Systec Inc., Korea), as shown in Fig. 1. Six different compressive forces (5, 10, 15, 20, 25, and 30 kg_F) were applied at a crosshead speed of 5 mm/min. Compressive forces of 5, 10, and 15 kg_F were applied using a 20 mm diameter cylindrical compression jig; forces equivalent to 20, 25, and 30 kg_F were applied by a 30 mm diameter cylindrical jig. Contact surface of both compressive jigs was flat surfaced platters.

3. Mathematical behavior of thermal waves

We consider an isotropic homogeneous semi-infinite solid target whose front surface is heated uniformly by a periodically modulated light source and surrounded by air. The distributed heat flux of the heat source is $(Q_0/2)[1 + \cos(\omega t)]$, where Q_0 is the intensity of the heat source, ω is the angular modulation frequency, and t is

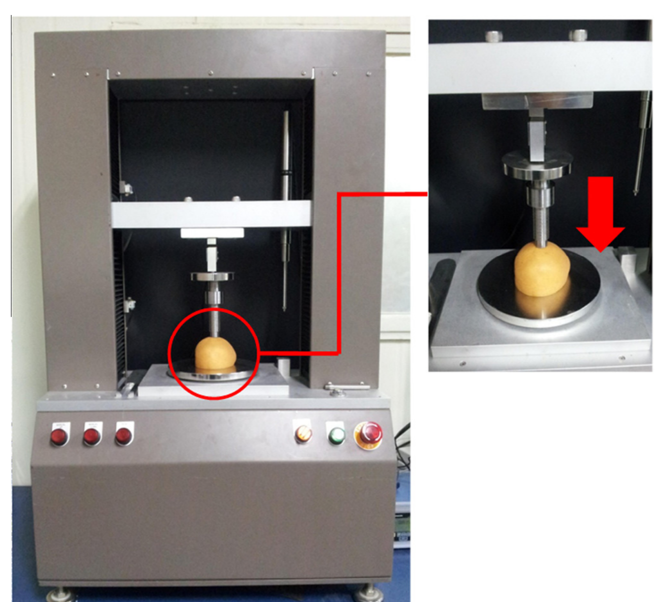

Fig. 1. Universal testing machine used in the application of force to create artificial damage to a pear.