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Detection of Compressive Damage on Persimmon using Infrared Lock-in Thermography

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Abstract

A lock-in thermography was used for the detection of compressive damage on persimmons. We measured the thermal emissions from persimmons using a highly sensitive mid-infrared thermal camera. Images were post-processed using a lock-in method that utilized the periodic thermal energy input. It was observed that the phase of thermal emission provides good metrics to identify quantitative information about both damage size and damage depth. A photothermal model was also implemented to investigate the behavior of thermal waves under convective conditions. Results suggested that the proposed lock-in thermography technique and phase information can be used to detect mechanical damage.

1. Introduction

Recently, nondestructive optical techniques have been proposed as an alternative to the conventional methods for detecting mechanical damage to fruits. New applications of infrared thermography for 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. In this study, we constructed an infrared 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 compressive damage on persimmons 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 persimmons 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 persimmons was performed using the phase difference between the damaged area and the intact area of each persimmon.

2. Material and methods

Selected persimmon samples were visually inspected to ensure that they were uniform, undamaged, and not infested by worms. After completing the naked-eye inspection, all persimmon samples were stored at a controlled temperature of 4°C and a relative humidity of 80% RH. In addition, persimmon 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. Persimmon samples were artificially damaged by compressive force using a universal testing machine (UTM), as shown in figure 1. Six different compressive forces (15, 20, 25, and 30 kg_F) were applied at a crosshead speed of 5 mm/min.

Fig. 1. *Universal testing machine used in the application of force to a persimmon*

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Fig. 2 shows a schematic diagram of the lock-in thermography system used for the thermal image measurement of damaged persimmon samples. This system consisted of a mid-infrared camera, halogen lamps, and a controller. Thermal images were taken with an infrared camera (SC7600, FLIR Systems, USA) that has a 640 × 512 pixel resolution and a sensitivity of 1.5–5 µm spectral range. The detector in the scanner unit was indium antimonide (InSb) and cooled by an integrated stirling cooler. Temperature sensitivity was 18 mK at 25°C. A lens with a 50 mm focal distance (IFOV: 0.3 mrad, spectral band: 3.5-5 µm) was used. Halogen lamps were operated by a control unit that controlled the periodic pulse on/off time.

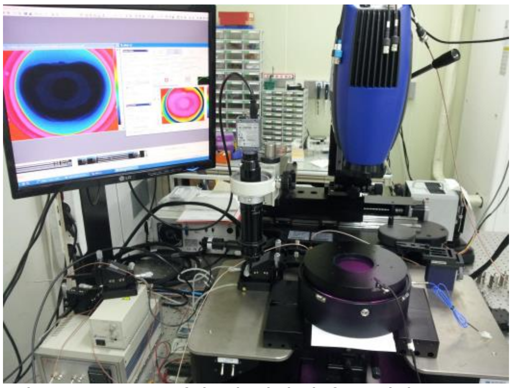

Fig. 2. *Experiments setup of the lock-in infrared thermography system*

The working principle of lock-in thermography is shown in Fig. 3. Periodic thermal waves propagate into the specimen and are reflected at the surface or subsurface in which the mechanical defects exist. The temperature modulation at the surface is modified by the thermal waves coming back from the inside of the material, and an oscillating interference thermal wave is produced. The IR camera then records the oscillating temperature by picking up a series of thermal images and reconstructs a periodic wave pattern using several signals with a step of *T/n* (where *T* is a lock-in period, and *n* is the number of samples per lock-in period). For the mathematical calculation of lock-in thermal signal, we applied the digital lock-in correlation procedure, which consists in averaging the product of the measured values and a set of weighting factors up to the total number of measured values. If the measurement is averaged over *N* lock-in periods, the digital lock-in correlation is expressed by the summation *S* as follows.

$$S = \frac{1}{nN}\sum_{i=1}^{N}\sum_{j=1}^{n} K_j F_{i,j} \quad (1)$$

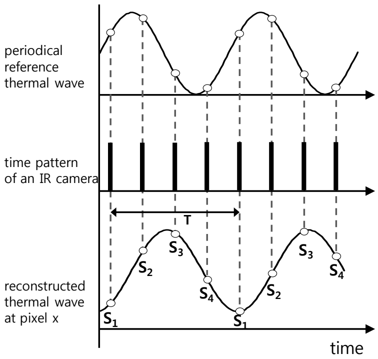

Fig. 3. *Working principle of lock-in thermography*

1. Results and discussion

3.1. Visual inspection

Fig. 4 shows visual images of the damaged persimmon samples for different compressive forces. CCD sensor-based vision inspection was performed shortly after applying the compressive force to persimmons to closely simulate the vision inspection conditions of early bruising on fruits. As shown in Fig. 4, quantitative estimation or detection of damages was not easy and the image contrast of defects on the persimmons was visually similar to each other except in case (d), which was compressed by 30 kg_F which was the maximum value among the adjusted loading forces. The vision test results again demonstrated that the CCD-based vision method used in existing automatic sorting systems still

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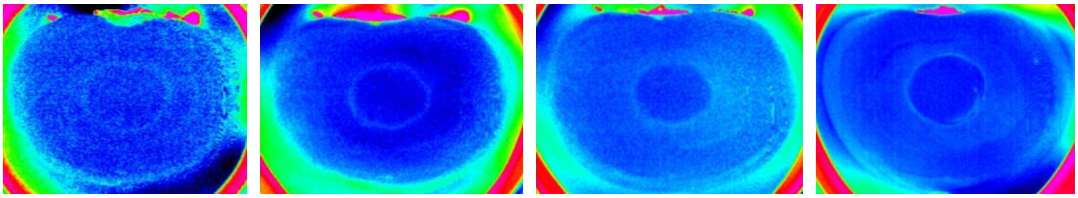
possesses insufficient precision for the accurate quantitative evaluation of bruising as well as depth estimation of defects, especially in detecting early bruises.

(a) 15 kgf (b) 20 kgf (c) 25 kgf (d) 30 kgf

Fig. 4. *Visual images of damaged persimmons using a CCD camera*

3.2. Phase Image Analysis

Registered thermal sequences were analyzed using the lock-in thermography technique. Fig. 5 shows phase images of damaged persimmons at a 0.1 Hz lock-in frequency. Damage size and location, which are not easily observed in Fig. 4, were clearly detected. These results indicated that the lock-in thermography technique can be used for the detection of damage on persimmon samples. In addition, it is well-established that the phase information from lock-in thermography is not influenced by reflections from heat sources, its illumination power, and sample shape.



(a) 15 kgf (b) 20 kgf (c) 25 kgf (d) 30 kgf

Fig. 4. *Phase images of damaged persimmons using a lock-in thermography technique*

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