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# Application of modal analysis to the watermelon through finite element modeling for use in ripeness assessment

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ABSTRACT

It is very difficult to judge watermelon ripeness by external characteristics. The laser Doppler vibrometer (LDV) is a new approach to determination of fruit quality. This optical-mechanical technique was utilized for nondestructive detection of the vibration response of watermelons to predict ripeness. Finite element modeling (FEM) was used to find the optimum location for excitation and response measurement and to analyze the mode shapes. The model was considered based on red, white, and green tissues and included individual properties such as density and elasticity modulus. Modal analysis of the finite element model showed acceptable agreement between experimental results and finite element simulation. According to the mode shapes of watermelon, optimum locations for applying input vibrations and detecting output vibrations were suggested. Then watermelons were excited and their responses were recorded by LDV at the determined locations. The phase shift between input and output signals were extracted over a wide frequency range. The firmness of cut fruits was measured with penetrometer as a ripeness indicator. A regression model was developed to predict the internal texture firmness using phase shifts at statistically selected frequencies. The determination coefficients ($R2$) of the calibration and cross validation models were 0.9998 and 0.994 respectively.



## 1. Introduction

Nondestructive quality determination of watermelons is a challenge for customers because their structure differs from that of other fruits. If it were possible for wholesalers to identify lower quality watermelons and remove them from the distribution system, this would result into increased consumer satisfaction. Common subjective methods are usually based on appearance or the sound produced by a slap. Neither of these is reliable as these methods are prone to human factor errors. Researchers have studied different objective methods to evaluate watermelon quality: acoustic and dynamic technology (Yamamoto et al., 1980; Stone et al., 1996; Armstrong et al., 1997; Diezma-Iglesias et al., 2002; Nourain et al., 2005), electrical and magnetic technology (Kato, 1997; Nelson et al., 2007), X-ray and computed tomography (Tollner, 1993), and near infrared (NIR) spectroscopy (Ito et al., 2002; Flores et al., 2008; Sun et al., 2010).

Muramatsu compared the accelerometer and LDV for measuring the firmness of some varieties of apple, pear, kiwi, and citrus. The measurements carried out using the LDV were more accurate than the accelerometer results (Muramatsu et al., 1997). Muramatsu also used the LDV method to determine fruit texture changes in persimmon, apple and kiwi during ripening. The phase shift significantly increased in the range of 1200–1600 Hz and the resonance frequency decreased in all fruit as a function of maturation (Muramatsu et al., 2000). The potential of measuring the vibration response with a laser vibrometer was studied for plums by Bengtsson. Phase shifts at selected frequencies were highly correlated to postharvest storage time, plum weight, plum length, and plum width (Bengtsson et al., 2003). Taniwaki also conducted separate investigations to review the trend of change in elasticity index figures from the melon, persimmon, and pear after harvest. The second resonance frequency of a sample was obtained using LDV. The samples were also evaluated by panelists, considering features such as appearance, sweetness, and firmness. (each separately). High correlations between the elasticity index and the mentioned properties were observed (Taniwaki et al., 2009a,b,c). The potential of LDV for ripeness assessment of the watermelon type 'Crimson sweet,' which is spherical, has been studied (Abbaszadeh et al., 2013). In this paper, laser Doppler vibrometry (LDV) technology is used to detect the vibration spectrum of watermelons.

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During LDV experiments, fruit positioning can affect results, especially for large fruits. Finding vibrational mode shapes is a useful tool to optimize the location of excitation and response detection in the LDV approach. It is appropriate to mount excitation and response instruments in the region away from nodal lines for detection of the vibration signal. The finite element method (FEM) is one of the numeric approaches used to solve differential equations such as those related to material deformation and mechanical vibration. In this method, objects are divided into many small regions called finite elements. With FEM, objects of irregular shapes and non-homogeneous material properties (e.g., density) can easily be modeled. Some researchers have applied finite element modeling for investigating the vibration characteristics of fruits (Chen and De Baerdemaeker, 1993a,b; Dewulf et al., 1999; Nourain et al., 2005; Song et al., 2006). The main objectives of our study were development of a finite element model for the watermelon (Charleston gray), determination of resonance frequencies and related deformations, and selection of optima for nondestructive assessment of watermelon quality by the LDV technique.

## 2. Materials and methods

### 2.1. Experimental determination of the natural frequencies

In this study thirty-five watermelons were selected for the experiments. The variety chosen was Charleston gray, a classic oblong with gray-green skin.

The experimental setup is presented in Fig. 1. Each fruit sample was placed on a shaker and excited with random wave signals (white noise) included frequencies from 0 to 1000 Hz. These input signals were computer generated and amplified by an amplifier. While the excitation signal was detected by an accelerometer (DJB A/120/VT, DJB Co., France) installed on a vibrational plate, the response of the fruit was optically sensed using a laser Doppler vibrometer (Model Ometron VH1000-D, Denmark).

The optical part of the LDV basically comprises a laser source, an interferometer, and one or several detectors. The LDV device emits a laser beam focused on a desired point on the upper side of the sample. The beam is then reflected from that point and returned to the LDV device. The operating principle is based on the Doppler theory that the frequency of a light beam reflected by a moving surface is different from its original value; the amount of frequency shift is called the Doppler frequency. The Doppler shift is proportional to the instantaneous speed of the vibration. In principle, it is possible to obtain the vibrating velocity of the surface by measuring the Doppler shift of the reflected light. The accelerometer and LDV signals are transmitted to the computer. A fast Fourier transform (FFT) algorithm is applied and the frequency responses of the fruit samples analyzed by considering the response signals and the exciting signals. The frequency response function spectrums were extracted for the entire frequency range. Using frequency response curves obtained by the accelerometer and LDV system, the resonance frequencies of the first three vibration modes were measured. The peaks of these resonances were well distinguished.

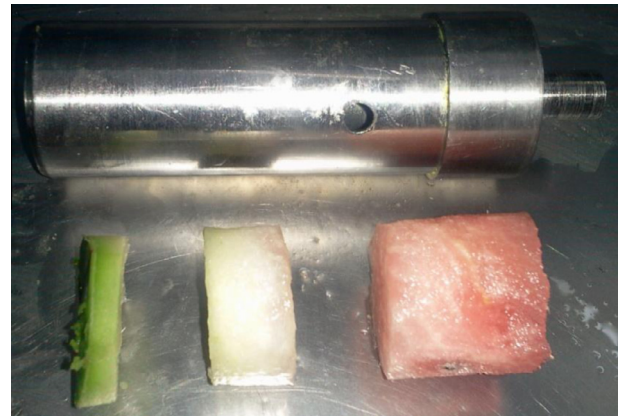

**Fig. 2.** Cylindrical sampler and pieces separated from red, white and green textures. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

### 2.2. Density measurement of watermelon textures

Before determining the frequency responses of watermelon models and comparing them with the results of LDV tests, it was necessary to measure the density of each tissue layer because the density is one of the important properties of the model. Thus samples were prepared from the red, white and green parts of the fruits. The density was calculated using the measured weight and volume. The device shown in Fig. 2 was used to obtain samples. A metal cylinder was attached to a handy drill to penetrate watermelons and provide samples. After samples were cut, different tissues were separated as shown in Fig. 2. To determine the volume, diameter and height were measured using a caliper. Twenty samples were removed from different parts of the watermelon to use for calculating density.

### 2.3. Finite element model and its modal analysis

To generate a finite element (FE) model, the geometry of the model must first be described. Therefore the major, intermediate,

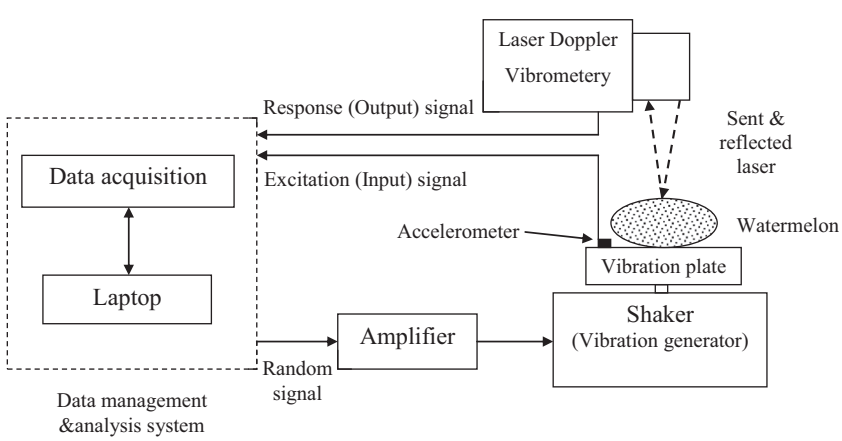


**Fig. 1.** Measuring vibration response of fruits by the LDV method.