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Research Article

Evaluation Performance of Ultrasonic Testing on Fruit Quality Determination

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There are several destructive and nondestructive methods for quality evaluation of agricultural products. Most of the employed traditional techniques are time-consuming and involve considerable degree of manual works. Destructive methods provide reasonable success rate of quality determination of fruits; however, they practically have many concerns about effectiveness, time, and cost. Therefore, developing portable, fast, and cost-effective techniques without harming fruits are desired for fruit quality evaluation. This work aims to develop a complete nondestructive quality evaluation system with (a) ultrasonic testing and (b) volume estimation by automatic machine vision techniques. The ultrasonic system consisted of a programmable bipolar remote pulser unit, a couple of piezoelectric probes for ultrasonic signal acquisitions as a transmitter and a receiver, an oscilloscope, and a computer. Visual appearance (size/volume) was determined using a machine vision system based on image processing techniques. Five different images of a fruit from different angles were captured by high-resolution digital cameras. Volume of the fruit was computed after horizontal and vertical distance of the fruit's images captured. The calculated volume values by the computer vision system are validated with the theoretical values. Although nondestructive ultrasonic estimation and volume estimation by image processing methods are cheap, fast, and practical, the results obtained in our experiments concluded that these methods are not as reliable as claimed in the literature.

1. Introduction

The quality (texture, color, shape, size, sugar content, and nutritional value) of agricultural products is highly important in terms of consumers, determining market acceptance, and thus, directly or indirectly affects storage and postharvest processing operations (such as transportation and conditions for storage) [1]. Therefore, these agro-food products should be harvested at optimum ripening stage, classified into different classes based on their quality parameters (firmness, color, size, and shape), and immediately transported to the market for consumers, as most of the vegetables and fruits are very sensitive agricultural products in over-ripening stages.

Destructive methods and professionally trained panels are widely used to determine the quality of fruits and vegetables. These methods are obviously more reliable; however, they are time-consuming and cost intensive and require specialized sample preparation. Therefore, the methods in this class are not suitable for industries such as packaging industry as it ruptures the fruit tissue and evaluation of whole lot cannot be done [2]. Trained panels are in another way abundantly used to evaluate quality of fruits and vegetables. Although well-trained panels make the evaluation, the scores can fall into a large variability and may drift over time. Moreover, the panel is generally limited to 6–8 objects per session, the procedure is slow, and the cost will be high [3].

The raising awareness of consumers in high quality of foods directs the producers to a reliable, rapid, nondestructive, and noninvasive technique for maturity determination, especially during harvesting and packaging processes. Therefore, in recent years, the application of

nondestructive, noninvasive, and noncontact methods and designing new instruments for food quality determination have been the focus of interest by researchers. These techniques are becoming more favored and practical compared to destructive techniques as nondestructive methods allow the measurement and analysis of individual fruit, reduce waste, and permit repeated measurements on the same item [4]. Different quality parameters have been determined in several agricultural products by a variety of nondestructive methods. These methods are based on optical, mechanical, electrical, and electromagnetic measurements [5, 6]. Nuclear magnetic resonance imaging (NMRI) [7, 8], Raman imaging [9], ultraviolet (UV), near-infrared (NIR), mid-infrared (MIR), e-nose [10, 11], ultrasonic technique [12], and machine vision [13] are some widely used nondestructive methods. Quality can be determined by evaluation of external and internal parameters of fruits. Firmness measurement is one of the most common methods used to determine maturity and/or ripeness. Evaluation of fruit ripeness or maturity is essential for timing in finding optimal harvesting, transportation-marketing, and consumption [2, 14]. Due to the fact that ripe fruit is very sensitive to mechanical damage, microbiological decay, and physiological deterioration, ultrasonic fruit quality evaluation can be a potential solution as a nondestructive system [15]. Ultrasonic technique has become a more common modality among other nondestructive methods for evaluation of fruits because of the advantages in firmness evaluation which are cost-effectiveness, robustness, reliability, and fruit safety [16–19]. The basic principle of ultrasonic measurement is considered as changes in attenuation and velocity of ultrasonic waves, namely, sound wave with a frequency higher than human hearing limit, by absorption and scattering of waves when interacting with a matter [20]. According to the literature, acidity, viscosity, and sugar content of fruits can be evaluated using the ultrasonic method by correlation of ultrasonic parameters with fruit inner factors. Velocity and attenuation are dependent on the physical parameters of fruits. Attenuation is also dependent on the frequency of sound propagation inside fruits [21–23]. Although the ultrasonic method is admitted as providing fast, accurate, and nondestructive fruit quality evaluation, currently developed ultrasonic systems are not suitable for nonlaboratory and field applications. Moreover, each fruit has a unique ultrasonic response but traditional ultrasonic systems are designed for specific fruit species. Our ultrasonic system gives the user the ability to change frequency, amplitude, and pulse repetition frequency as well as the number of pulses in a burst. Moreover, the system we used in this experiment differs from other devices used in the market by producing positive, negative, and bipolar pulses and changing the frequency settings from 10 kHz to 10 MHz. The devices in the market produce frequencies starting from the lower limit of 500 kHz. This frequency is too high for fruit quality measurement as frequency increases, penetration decreases, and general losses increase. Therefore, the custom-designed ultrasonic system is crucial to monitor the quality of different types of fruits in picking, storing, and packaging site in addition to laboratory-based applications.

Nondestructive ultrasonic method itself is not enough to determine the fruit quality using internal parameters. It is essential to use a proper method to obtain the physical characteristics of fruits in terms of size, shape, and volume as well. Nondestructive custom-designed ultrasonic system combined with a noncontact physical measurement unit can provide superior quality assessment of fruits.

Intensive researches have been conducted to design and build computer-aided machine vision system for a variety of fruit samples, and promising results of machine vision system for fruit quality have been shown [24–29]. For this purpose, image processing techniques, which are intelligent, feasible, cost-effective, and easy-to-use machine vision system, are mostly used for sorting and grading of fruits based on size, volume, and shape. Our computer-aided machine vision system has basically three steps for fruit sorting and grading: (1) firstly, images of fruits from different angles are captured by high-resolution cameras; (2) secondly, required features are extracted from the captured images by image processing techniques, and (3) finally, volume is estimated using extracted features. The system developed in this study has the capacity to give more detailed information about the physical (external dimension) and internal (inner sugar content, acidity, etc.) properties of the fruit. Therefore, fruit sorting and grading with high accuracy based on predetermined features, ultrasonic and visual, of fruits can be achieved using machine learning methods using our customized systems.

The aim of this study is to introduce a nondestructive system integrated with ultrasonic and machine vision methods for fruit quality evaluation. This system is eligible to monitor the maturity of tomato, peach, apple, and apricots and evaluate volumes. Although the ultrasonic system integrated with automatic machine vision could provide more accurate fruit quality assessment, our results showed that quality assessment of fruits using ultrasonic methods using through transmission (TT mode) technique has drawback in terms of reliability. Experimental results of this study conflict with the results in the literatures. Therefore, we concluded that more studies are required to confirm the reliability of the ultrasonic system for fruit quality assessment.

2. Materials and Methods

In this study, two methods, including ultrasonic measurement and image processing-based machine vision measurement, were used to evaluate the fruit quality based on external and internal parameters of fruits. These methods are explained in the following sections.

2.1. Ultrasonic System Setup. Developed ultrasonic system performance was tested before measurements. Experimental setup as shown in Figure 1 was used to confirm system reliability and accuracy. Two ultrasonic probes with 1 MHz were used for transmission and reception of ultrasonic signals. One of the probes was transmitter and the other was receiver.

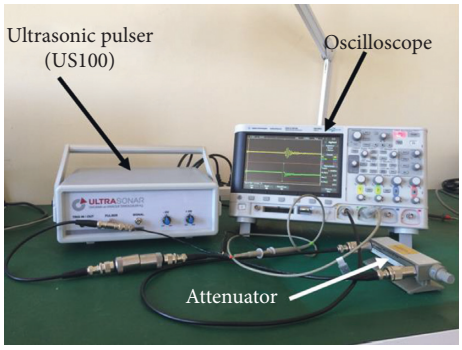

Figure 1: Experimental setup to show ultrasonic system reliability.

The 167 V_{PP} signal including 1, 2, and 3 pulses were applied to the transmitting probe using a pulser (US100). The receiving probe was connected to the oscilloscope (model: Agilent DSO-X 2014A 100 MHz), and the received signal was attenuated around 10 dB (model: Keysight 8496A 110 dB) to make more clear signal visibility on the oscilloscope. The received signal amplitudes were 10.7 V_{PP}, 18.7 V_{PP}, and 23.1 V_{PP}, respectively. These results are shown in Figure 2. According to these results, it is said that the systems are working properly.

Figure 3 shows the experimental system we used for measuring velocity and attenuation of ultrasonic signals for fruit quality measurements. The system consisted of two ultrasonic transducers, fruit samples (apple, tomato, apricot, and peach), an ultrasonic pulser unit, an oscilloscope (Agilent 2014A), and a personal computer (Intel Core i7). In this study, a special ultrasonic pulser unit (US 100) was designed and implemented [30, 31]. This customized remote pulser unit has four main components: (1) power supply unit, (2) microcontroller unit (MCU), (3) interface unit, and (4) MOSFET unit. The remote pulser can be controlled by a PC over the USB port. Variety ultrasonic parameters are easily tuned in this system. Depending on the applications, frequency, pulse repetition frequency (PRF), number of pulses in a burst, starting pulse (positive or negative), and triggering option (internal or external) all can be set by the user. 55 kHz low-frequency ultrasonic probes were used for ultrasonic wave transmission and reception in addition to high penetration of ultrasonic waves from the fruit's surface (shell) into the fruit. Through transmission (TT) technique was used for measurement of ultrasonic velocities and attenuation of transmitted signals. Fruits were placed between two transducers; the transmitting transducer was excited with the pulser unit, and it generated ultrasonic longitudinal waves passing through the whole fruits. Voltage, frequency, PRF, and starting pulse of the pulser were setup as 180 V_{PP}, 55 kHz, external trigger, and positive starting pulse, respectively. The transducers are coupled to fruits with an ultrasonic gel in order to increase the amount of ultrasonic power that penetrates the fruit. The receiver probe was used to collect back-attenuated signals that passed through the inspected fruit and connected to the oscilloscope in order to visualize and measure the attenuated signals. The first experimental result of the fruit quality measurement using the customized remote pulser unit has been found [32].

2.2. Machine Vision System. The components of the machine vision system are five high-resolution cameras, a 50 W LED light source, and a sample holder. Connections of cameras to PC were achieved over the USB communication port. Cube-shaped white box ($40 \times 40 \times 40$ cm) made of wood was fabricated in the laboratory to cover the experimental system and eliminate unwanted light sources from outside as shown in Figure 4. Cameras are mounted on five sides of the box, except the bottom surface. Each fruit was placed at the center of the camera's field of view, and five RGB color images were captured and saved in jpg format. Captured images have a pixel of 1280×960 resolution. The captured images were segmented from the background using a simple thresholding method combined with morphological operations in each image. Feature extraction process (major and minor axis lengths) was accomplished following segmenting the fruit sample from the background. The volume of the fruit was calculated by considering the fruit as an axisymmetric object. Detailed description of volume estimation used in this study was explained in our previous study [13].

3. Results and Discussion

Two different schemes have been designed for TT mode ultrasonic experimentation. Fruits with and without shell have been exposed to the ultrasonic signal. According to the experimental results, the ultrasonic signal is strongly reduced due to absorption while the signal passes through the fruit. As it can be seen in Figures 5(a) and 5(b), no signal measurement was observed by the receiving probe. Even under the signal which has a high signal amplitude (e.g., 120 V), the signal measurement that can pass through the fruit was not possible.

The porous-uneven surface and pericarp of the fruit result in scattering of ultrasound, and this thereby prevents the transmission of the ultrasonic signal. Because after the fruits were peeled and ultrasound applied to the peel, the receiver probe could have measured the attenuated signal (Figures 5(c) and 5(d)). Application of the ultrasound signal with a focus was considered as a solution; the ultrasonic system with a horn, however, is not a common method for nondestructive fruit quality measurement. In this study, the main purpose of using horn is to achieve high-intensity ultrasound in the fruit surface. We have designed and fabricated ultrasonic horn as described in [33]. We assumed that signal intensity was not enough for measurement in the case of ultrasonic probe with flat surface because the ultrasonic signal propagates the fruit surface rather than a specific point. Thus, we can say that the horn was used to confirm whether the applied ultrasonic signal intensity is enough or not for successful measurement. However, experimental results showed that no received signal was measured with and without the ultrasonic horn.

To do that, ultrasonic horns made of aluminum are designed and manufactured. The inside portions of these horns are empty; therefore, they are filled with ultrasonic gel during the application to reduce signal loss. Measurements were repeated with the horns mounted at the ends of the receiver/transmitter probes. After assembly, the probes were

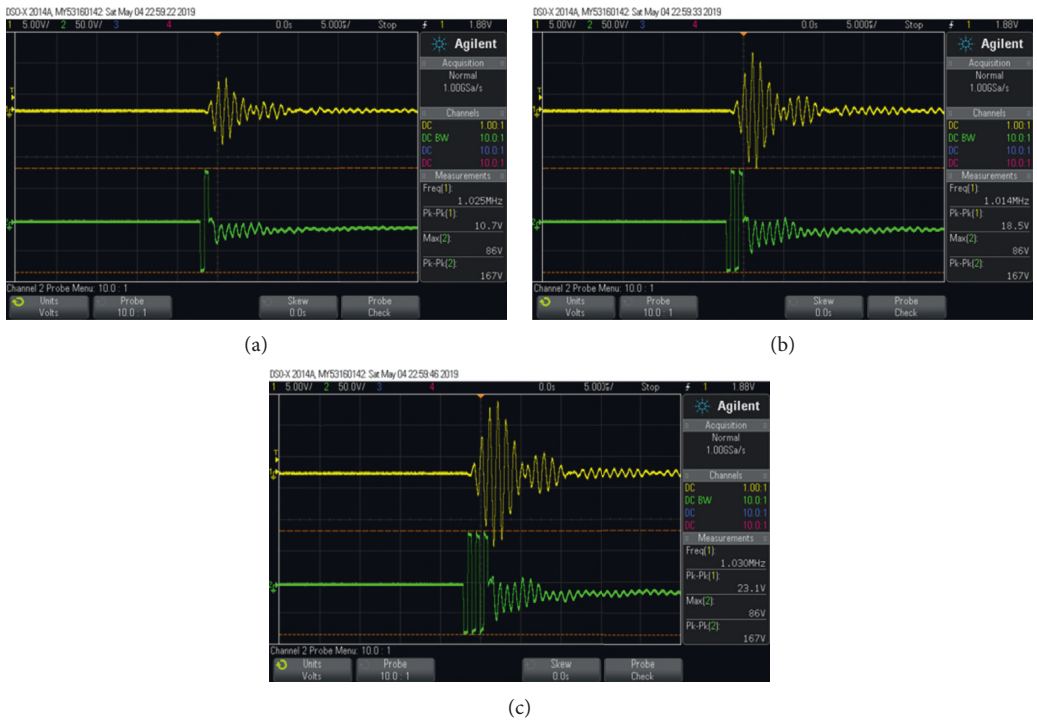

Figure 2: Transmission and reception performance of the ultrasonic system that received signal (a) 10.7 V_{PP} for 167 V_{PP} input signal with single pulse, (b) 18.5 V_{PP} for 167 V_{PP} input signal with two pulses, and (c) 23.1 V_{PP} for 167 V_{PP} input signal with three pulses.

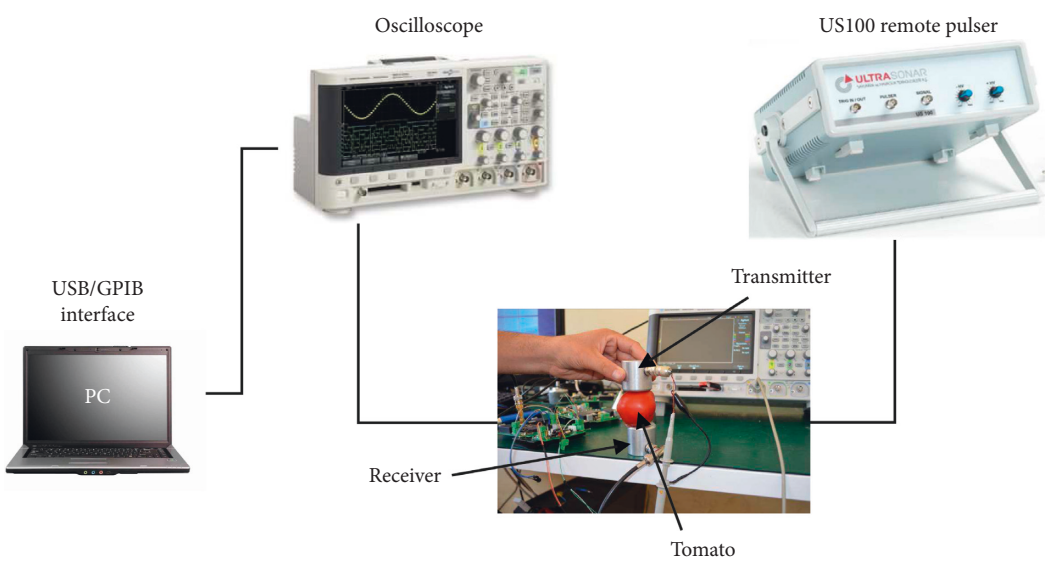

Figure 3: The schematic view of the ultrasonic measurement experimental setup.

tested by contacting each other, and the received signal was observed on the oscilloscope. However, when the measurements were repeated on the fruits, the same result was not observed as shown in Figure 6. The attenuated signal cannot be measured in either case.

In the literature [21, 34–36], the most commonly used frequency value is 50 kHz for TT mode measurements. However, even 55 kHz frequency used in this study did not provide similar results mentioned in the literature. Although the signals produced were also applied with horns, there was no change in the measured results. If very thin slice of fruit is used instead of whole fruit, the results in the literature may be obtained. Because, as it is known, the absorbed distance varies exponentially ($A = A_o e^{-\alpha x}$) and consequently the attenuated signal amplitude (A) is inversely proportional to absorption ($e^{-\alpha x}$). In this case, quality determination of the whole fruit by the ultrasound method in the TT mode is not very logical. Although ultrasound is a safe tool for the

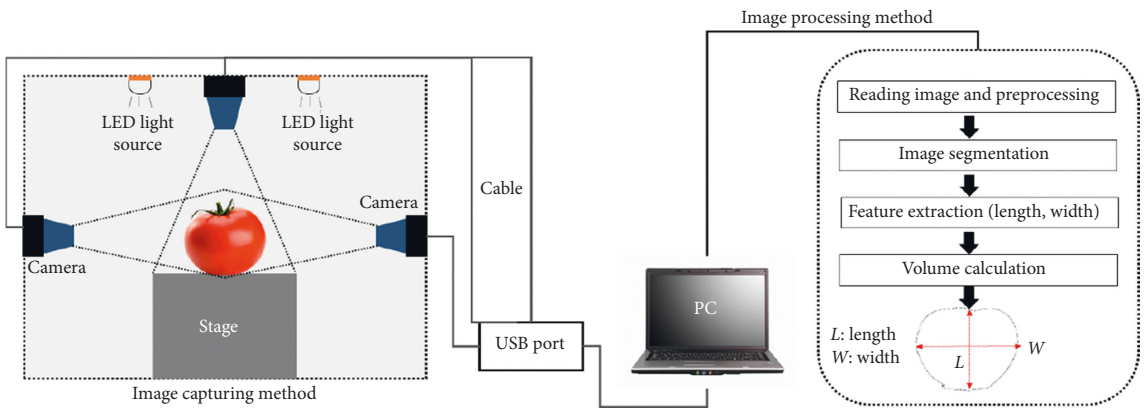

Figure 4: The proposed machine vision system for fruit volume calculation [13].

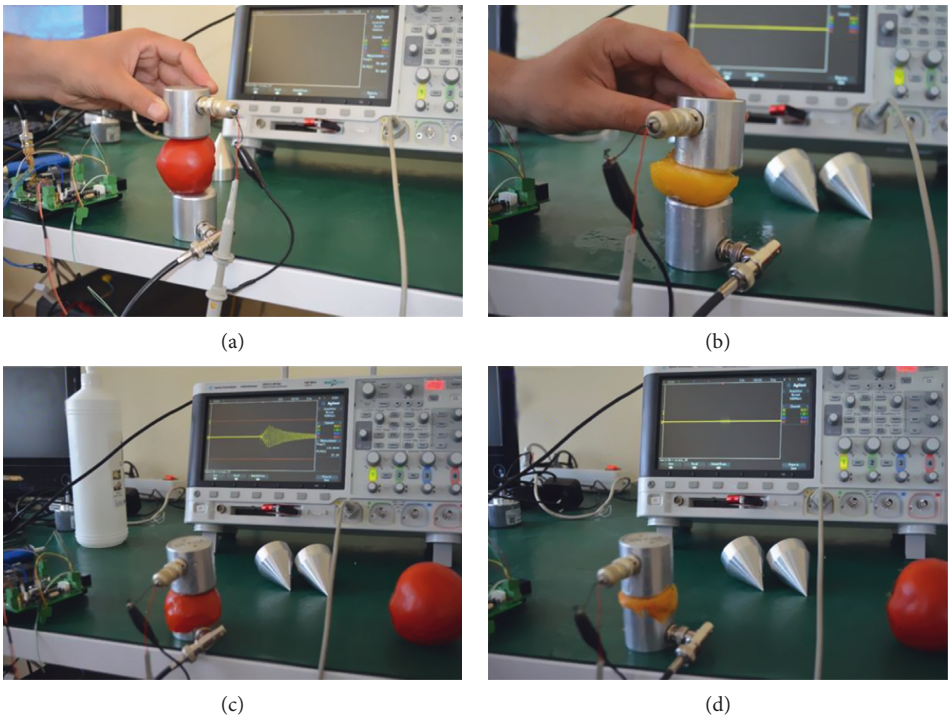

Figure 5: Ultrasonic testing of fruits: no signal was observed in (a) a tomato with skin and (b) an apricot without skin. Receiving probe can collect transmitted signals when the shell of (c) a tomato and (d) an apricot was used for experimentation, respectively.

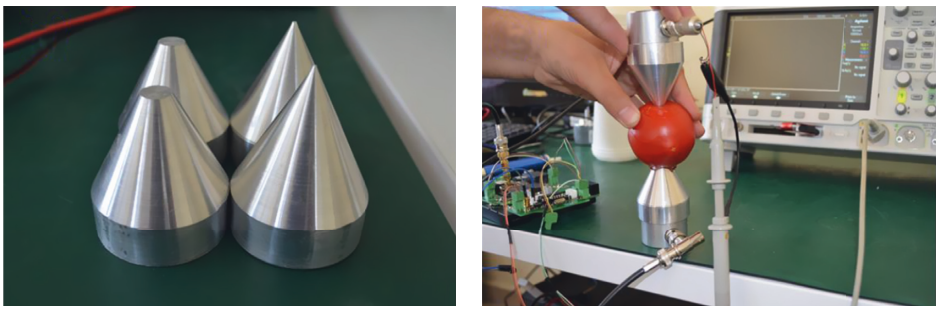

Figure 6: (a) Fabricated ultrasonic horns to focus ultrasonic signals; (b) no signal passed through the whole fruit when the transmitted signal was focused using the horn.

measurement of the fruit in the TT mode, the experimental results are problematic in terms of reliability.

In this study, the machine vision system developed in our previous study was used, and successful results were obtained in determining the size of the fruit [13]. This system is practical and easy to use in determining the physical properties (surface area/volume) of fruits even though it is not sufficient to determine other quality characteristics such as firmness.

However, in contrary to the literature, the TT mode ultrasonic system is not a reliable method in determining the quality of fruit due to the aforementioned reasons. In the future studies, the PE mode ultrasonic method will be used as an alternative to TT mode ultrasonic measurement. Ultrasonic waves reflected from the fruit shell will be measured, and the quality of the fruit will be obtained by designing a T (transmission)/R (reception) switch for the PE system.

4. Conclusions

The TT mode ultrasonic system has been developed for fruit quality determination. In addition to the ultrasonic system, image processing based on the machine vision system was used to determine the quality of the fruit.

First of all, the outer characteristics (size and volume) of the fruits were determined by the machine vision system. This technique consists of multiple cameras which is much more practical, unlike the conventional method in which images are captured from a single camera and fruits have to be rotated by the hand. More accurate results may be obtained by reducing unwanted noise (shadows) in the images.

Secondly, expected results could not be obtained with the ultrasonic system developed to determine the fruit quality using the correlation between ultrasound parameters and the properties of the fruit. According to our results, TT mode ultrasonic measurement is not possible, although it is mentioned in the literature that the quality of fruits can be determined with the same method. Therefore, both PE mode ultrasonic system and machine vision system can be more efficient tool in determining the fruit quality. Therefore, this study may lead to more intensive study and development of PE mode applications of ultrasonic systems in order to determine the fruit quality.

Data Availability

Previously reported results of our image vision system were used to support this study and are available at doi: 10.1109/EBBT.2018.8391460. This prior study was cited at relevant places within the text as reference [13]. Figures used to support the findings of the ultrasonic nondestructive measurement in this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Authors' Contributions

Fikret Yildiz, Ahmet Turan Özdemir, and Selman Uluışık proposed the research topic, supervised the study, and prepared the initial draft of the manuscript together. Fikret Yildiz contributed significantly to the writing and organization of the manuscript. Ahmet Turan Özdemir mostly coordinated the experimental work and analyzed the experimental data in Ultrasonar Defense and Aviation Technologies Inc.

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