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Ultrasonic technique for non-destructive quality evaluation of oranges

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ABSTRACT

Common techniques to monitor the quality of fruit at the time of harvest and in storage typically rely on destructive methods to measure physical properties such as firmness and hydration. The complex, inhomogeneous composition of most fruit mean that non-destructive ultrasonic methods for quality evaluation of fruit has typically been unsuccessful. A novel ultrasound method was developed which analyses the reflections at the transducer-fruit boundary to evaluate the quality of the fruit as a whole. Using a custom-built ultrasound device, the technique was applied to navel oranges to relate ultrasonic measurements with physical measurements taken via destructive methods. For a sample of randomly selected navel oranges, a high level of correlation was found between ultrasonic measurements and the density of the fruit, allowing the relative water content of oranges to be non-destructively determined regardless of individual physical characteristics such as size and maturity. When applied to a sample of navel oranges over a period of nine days, the ultrasonic measurements were found to be highly correlated to the firmness of the oranges, providing a non-destructive method to replace traditional destructive methods currently used to monitor orange maturation.

1. Introduction

Due to seasonal variations, a large percentage of worldwide fruit crops are kept in storage for extended periods of time, before distribution for sale in different countries (Camarenta and Martinez-Mora, 2006). In such a situation, it is critical to be able to easily and reliably measure the quality of the fruits, so that optimal conditions for maturity and freshness can be met, and to dispose of sub-standard (dry, over-ripe, etc.) fruit. Where fruit is not being moved to storage, it is also beneficial to be able to measure these properties *in situ* before or at the time of harvesting.

Although a number of factors come into defining overall fruit quality, common physical indicators include firmness, which is typically measured destructively using penetration tests (Abbott, 1999) or parallel plate compression (Valero et al., 2007; Pallottino et al., 2011), and hydration (Camarenta and Martinez-Mora, 2006). Such methods are unable to detect fluctuations in fruit quality within a single batch, as only a small fraction of the fruit can be tested with destructive methods. Hence, an automatic and non-destructive method for quantitatively determining fruit quality would be of great economic benefit to the agriculture industry.

By and large, the use of traditional ultrasonic methods on fruit has been unsuccessful as their acoustic properties were not understood (Mizrach, 2008). Pores and inter-cellular voids in the fruit's flesh cause ultrasonic waves to be scattered, causing attenuation to be several orders of magnitude greater than that in air (Javanaud, 1988), making ultrasonic results difficult or impossible to analyse (Povey, 1998).

Examples of ultrasonic measurements on a wide range of fruit and vegetables can be found in Watts and Russell (1985), Povey (1998), Mizrach et al. (1989), Mizrach et al. (2000), Camarenta and Martinez-Mora (2006) and Mizrach (2008). It has so far proven impossible to perform ultrasonic transmission through entire fruit or vegetables due to the high levels of attenuation. Methods which have been successful in performing ultrasonic measurements on fruit have been generally limited to using cumbersome lab-based devices, with experiments performed destructively on segments of fruit, rather than the whole. Few methods have proven successful in determining fruit and vegetable quality using ultrasonic techniques.

Using a high-power ultrasound device designed for concrete analysis to overcome the thigh attenuation, Mizrach et al. (1989) were able to successfully measure the reflective loss, velocity of propagation and attenuation through a variety of cylindrical samples up to 20 mm in length for various fruit and vegetables. Performing the transmission method through orange peels, Camarenta and Martinez-Mora (2006) determined a relationship

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between the acoustic properties of the orange peel and the physical characteristics (firmness and dehydration) of the overall fruit.

The most successful ultrasonic measurements of fruit and vegetables have been gained using surface wave transmission techniques. In these experiments, two fine-tipped ultrasonic transducers were angled towards each other, close together (5–18 mm) on the surface of the sample, and the attenuation and velocity of propagation were measured between them (Mizrach, 2008). The results showed a strong correlation between the attenuation of the ultrasonic waves and the firmness and dry weight (measured using destructive techniques) of avocados, mangoes, apples, melons, plums, potatoes and tomatoes.

The disadvantage of two-transducer ultrasonic methods is that the transducers must be properly aligned, making such methods difficult to apply automatically or in a non-laboratory environment.

Single transducer pulse-echo techniques of fruit and vegetable internals prove impossible as attenuation is twofold due to the extra distance which must be travelled.

This paper presents a novel, single-transducer method for determining fruit quality, which can easily be applied automatically or in the field.

2. Instrumentation

2.1. Ultrasound hardware

Prior research into the ultrasonic testing of fruit has often been hindered by the use of generic ultrasound equipment, which is not necessarily suited for use on fruit. In order to overcome the limitations imposed by using ill-suited equipment, a custom ultrasonic device was designed and manufactured by researchers at the University of Queensland with the specific purpose of ultrasonic testing of fruits. The design of the device, pictured in Fig. 1, took into consideration findings from previous research into ultrasonic testing of fruits, as well as economic viability in an agricultural setting. Whereas traditional ultrasonic equipment can cost upwards of $1000, the device was built for under AU$150 (not including a transducer), making large-scale use in the agricultural industry more feasible.

Previous research (Sarkar and Wolfe, 1983; Povey, 1998; Mizrach, 2008) suggests that ultrasonic frequencies less than 200 kHz yield best results when applied to fruit, as the increased wavelength minimises the effect of scattering caused by resonance of inter-cellular voids in the fruit's flesh. The device was designed with this constraint in mind, and as such, the lower frequency allowed the electronic design to remain relatively simple, as high frequency transmission line effects were minimised compared to higher frequencies.

As reliable transmission ultrasound through whole fruit had so far proven problematic, the primary focus for research was low-power, surface-based ultrasonic techniques. For this, two 9 V PP3 type batteries were sufficient to power the device, which also allowed it to be portable for possible field use. A MOSFET based ultrasonic front-end was used to drive the transducer output with a regulated 30 V peak-to-peak square signal.

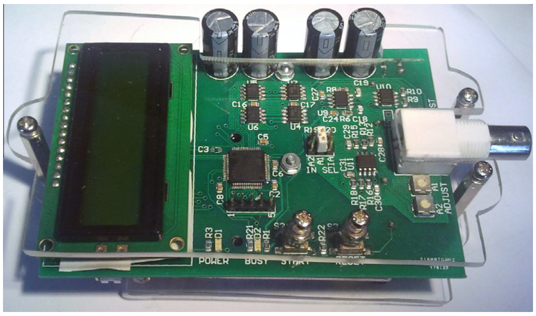

Fig. 1. Custom-built ultrasound device for fruit quality evaluation, with clear case to show electronic design.

The return signal is buffered using a high-sensitivity instrumentation amplifier and captured using a 12-bit analogue to digital converter (ADC) at a rate of 3 million samples per second. Digital signal processing (DSP) techniques were used to analyse the recorded return signal, in favour of analogue equivalents in hardware, allowing the device to be easily adapted to use different signal processing techniques.

An on-board ARM microcontroller (STMicroelectronics STM32-F4) was used to generate waveforms for driving the transducer, and for recording and processing the return path signal. Signal processing could be performed on the device itself, making it completely self-contained, or transmitted to a PC via USB for manual analysis.

2.2. Ultrasound transducer

A 100 kHz contact transducer, model GRD100-D25, from Ultran Group® was used. The transducer was used without a delay line. Using the custom ultrasound device, the reflected impulse response from a 30 V negative spike was recorded in water with a steel reflector. The Fast Fourier Transform (FFT) of the impulse response was used to determine the frequency response of the transducer. Both are shown in Fig. 2.

From Fig. 2, the frequency characteristics of the transducer were a 102 kHz centre frequency with a 37 kHz −6 dB bandwidth. The transducer is impedance coupled to water, with an acoustic impedance of 1.48 M Rayls.

2.3. Digital scales

Unless otherwise specified, mass measurements were taken using an iBalance M01 with a precision of 0.01 g.

3. Ultrasound analysis technique

A novel pulse-echo based ultrasound analysis technique (the technique) was developed specifically for analysis of fruit, which uses ultrasonic echoes close to the surface of the fruit and from

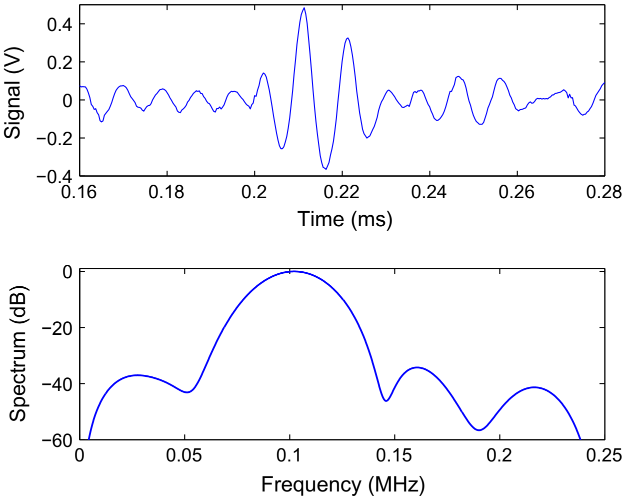

Fig. 2. Impulse response (top) and frequency response (bottom) of ultrasonic transducer.

the transducer-fruit boundary itself to classify the overall properties of the fruit.

The pulse-echo technique uses reflections of ultrasonic energy from boundaries of differing acoustic impedance to identify the physical composition of the medium. The ratio of reflected to total incident ultrasonic energy at a such a boundary is given by:

$$\Gamma = \frac{(Z_1 - Z_2)^2}{(Z_1 + Z_2)^2} \tag{1}$$

where Z_1 and Z_2 are the acoustic impedance of the medium (measured in Rayls) either side of the boundary.

Usually, a coupling gel is used to minimise the impedance mismatch between the transducer and the medium by creating a homogeneous layer through which the generated ultrasonic energy is conducted into the medium. Without coupling gel, microscopic air pockets exist between the transducer and the medium, resulting in a large acoustic impedance mismatch. By Eq. (1), this causes a portion of the ultrasonic energy to be reflected back into the transducer, while the remainder is transmitted into the medium.

The technique used analyses reflections from fruit under dry coupling (without coupling gel) conditions to assess the acoustic and physical properties of the fruit. When the transducer and fruit are held in contact with one another under dry coupling conditions, the transducer is partially coupled to the medium. As such, the overall acoustic impedance mismatch at the boundary of the transducer is influenced by the fruit's acoustic and physical properties, allowing these properties to be measured without the need for the ultrasonic signal to propagate within the medium itself. Camarenta and Martinez-Mora (2006) performed experiments on oranges which showed a strong relationship between the ultrasonic properties of the orange peel (velocity and absorption) and physical properties of the whole fruit, specifically dehydration and firmness. With this in mind, the technique was used to examine the orange peel to determine the overall properties of the fruit. This is especially advantageous in this case, as ultrasonic signals internal to the fruit would be subjected to high levels of attenuation and dispersion.

Fig. 3 gives an example of the recorded ultrasound reflections from a navel orange under dry coupling conditions, showing the initial impulse response of the transducer and subsequent reflections of ultrasonic energy.

By integrating the magnitude of the recorded time domain signal, the quantity of reflected energy between the transducer and the medium can be determined. The limits of integration were determined based on the constant location of the reflected waveform in the echo signal, from 0.025 ms to 0.11 ms after driving the transducer, as indicated in Fig. 3. The results are given as the ratio of incident to reflected energy at the transducer. The incident signal, two periods at 100 kHz, can be seen in the first 0.02 ms of Fig. 3.

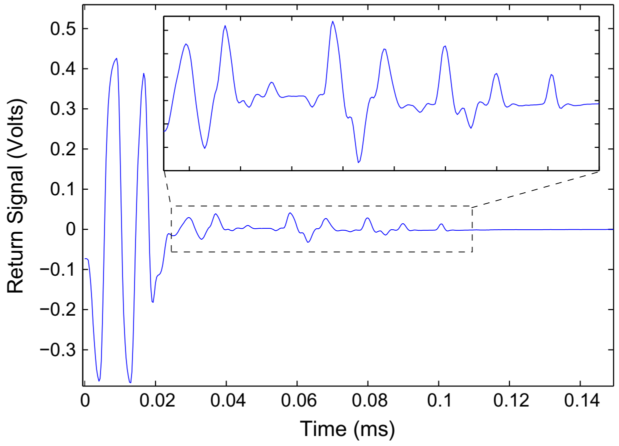

Fig. 3. Example of the recorded ultrasonic signal, showing the initial impulse response of the transducer and subsequent reflections.

As acoustic impedance is defined as the product of density (ρ, in kg/m^3) and acoustic velocity (c, in m/s) (Subramanian, 2006):

$$Z = \rho c[\text{Rayls}] \tag{2}$$

the total reflected energy (RE) can be directly related to the density of the medium being imaged by adapting Eq. (1):

$$RE = G\frac{(Z_1 - \rho_2 c_2)^2}{(Z_1 + \rho_2 c_2)^2} + C[J/J] \tag{3}$$

where G is a unitless scaling factor introduced by the numerical integration and quantization of the signal, and C represents the energy reflection due to the impedance mismatch caused by the dry coupling environment. Both terms of Eq. (3) relate to physical properties of the medium. The first relates directly to the acoustic impedance, and hence density, of the medium, while the second represents how well the medium conforms to the transducer, i.e. a more conforming medium will minimise the air gap and resulting reflections from the transducer boundary.

4. Experimental methods

4.1. Effect of transducer coupling force

For the technique, the force with which the transducer is coupled to the medium affects the quality of the coupling at the transducer-fruit boundary. Increasing or decreasing the transducer coupling force will cause the second term of Eq. (3) to decrease or increase respectively. However, assuming all other parameters remain constant, the first term of Eq. (3), which represents the acoustic properties, will remain largely unchanged irrespective of the coupling force that is applied. Therefore, if the coupling force is unchanged between measurements, it is expected that the measurements from any number of samples will remain constant relative to one another, allowing the acoustic properties of the samples to be directly compared.

To illustrate the effect of transducer coupling force, the technique was applied to five navel oranges. Each of the oranges was selected to represent an extreme case, with varying sizes (77–96 mm average diameter), ages (0–2 weeks post-harvest) and peels which ranged from smooth to rough and porous. Ultrasonic measurements were taken on each orange with the transducer being pressed against the equator of the orange with forces varying from 25 N to 50 N in 5 N increments. For each applied force, four measurements were taken at equally spaced points around the equator of the orange and averaged.

4.2. Relative water content

Fruit from the same crop will not always share physical characteristics, so the destructive measurement techniques which are applied to only a small fraction of fruit in storage are unable to identify individual sub-standard specimens within a single batch.

The technique was used to non-destructively determine the relative hydration of a sample of oranges. 20 navel oranges of varying size, maturity and skin texture were selected.

The density of the oranges was used as a physical measure of hydration, as an orange with a higher water content will have a higher density (closer to 1 g/cm^3), whereas a dry or mealy orange will have a lower density. The density of each orange was calculated as the ratio of mass to volume, where the volume was determined by submerging each orange in water on a zeroed scale and observing Archimedes' principle. This method was chosen over other displacement methods as it is not affected by visual measurement errors caused by the meniscus of the displaced medium, and as such makes full use of the scale's precision.

Ultrasonic measurements were taken at four equally spaced points on the equator of each orange and averaged, to account for any discrepancies caused by imperfections on the skin which may affect coupling between the transducer and the fruit. A constant force of 35 N was applied between the transducer and the fruit. As the force is decreased, the quality of the coupling between the transducer and the fruit is negatively affected, resulting in the steep increase in reflected energy shown in Fig. 4. However, above 35 N, further increasing the force has less effect on the quality of coupling but does contribute more to the physical deformation of the fruit. Hence, 35 N was chosen as it presents a good balance between the quality of coupling and the force applied to the fruit.

4.3. Firmness and dehydration

In addition to differentiating between the quality of individual oranges, the maturation of oranges in storage must be tracked to ensure that optimum conditions for ripeness are maintained.

75 recently harvested navel oranges were sourced from a local supplier. The oranges were selected based on their similar size and level of maturity, and had not been subjected to any chemical treatment. Over a period of nine days, the oranges were kept at ambient conditions, with temperatures ranging from 7 °C to 23 °C and relative humidity of 31% and 83%. At the start of the experiment, the mass and surface area of each orange was recorded.

The surface area was calculated by measuring the circumference of each orange over three perpendicular axes and modelling the fruit as an ellipsoid. Using the circumferential measurements, the volume of each orange was also calculated by the ellipsoid model and compared to actual volume measurements taken using the displacement method described previously. On average, the variation between the calculated and measured volumes was no more than 5.3%, implying that the error in the surface area calculations is no more than 3.5%.

On five out of the nine days, 15 oranges were selected at random and their mass, firmness and ultrasonic reflection were recorded. Ultrasonic measurements were taken using the same method described in Section 4.2. The firmness of the oranges was tested by measuring the force required to compress the oranges to 95% of their original equatorial diameter between two parallel plates. Firmer oranges exhibit a higher resistive force to compression. The force was measured to a precision of 0.1 N.

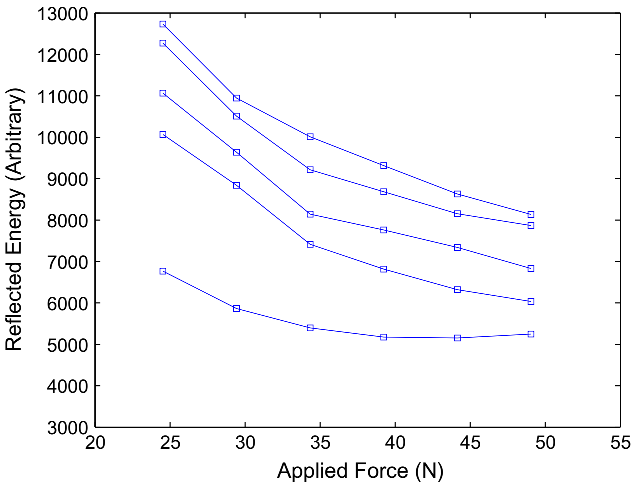

Fig. 4. Comparison of results for varying transducer coupling force.

Using the recorded mass (W, in kg), the dehydration (D) (the loss of weight due to evaporation) was calculated by:

$$D = \frac{W_{initial} - W_{current}}{S} \quad [\mathrm{kg/m^2}] \qquad (4)$$

where S is the surface area of the orange in m^2.

5. Results

5.1. Effect of transducer coupling force

Fig. 4 shows the reflected energy for 5 navel oranges the ultrasonic transducer being applied with varying force.

25 N was the minimum force required for the face of the transducer to come completely in contact with each of the oranges. Below this range, where the transducer is not fully contacting the sample, spurious results are encountered. At and above 45 N, the force was sufficient to permanently deform the oranges, which is inappropriate for a non-destructive testing regime.

Oranges with differing physical characteristics were chosen so that the reflected energy patterns were easily distinguishable over a wide range, to best illustrate the effect of varying transducer coupling force. As the force was increased, the reflected energy for each orange decreased as a result of improved coupling between the transducer and the fruit, effectively lowering the second term of Eq. (3). However, as the acoustic properties of the oranges are not altered by the change in force (i.e. the first term of Eq. (3) remains constant), the results from each remain constant relative to one another regardless of the force which is applied. As long as the transducer coupling force is applied consistently, any number of samples can be directly compared based on their acoustic properties alone, as the ultrasonic energy returned from the imperfect coupling boundary will remain constant for each.

For future experiments, a constant force of 35 N was applied to the transducer. This force presents at a knee-point in Fig. 4, where decreasing the force has a more significant impact on the reflected energy while increasing the force has a less significant effect on the results but increases the potential to cause permanent physical damage to the samples.

5.2. Relative water content

Fig. 5 shows the reflection coefficient for 20 navel oranges of varying densities. The reflected energy (RE) results collected directly using the technique are influenced by a number of physical factors, such as the firmness of the fruit, uniformity of the peel and the transducer coupling force. To represent the results as a function of acoustic properties only, the Curve Fitting tool in MATLAB® was used to determine the constants G and C in Eq. (3), allowing them to be removed algebraically, giving results directly in terms of the reflection coefficient (Γ) in the form of Eq. (1), representing the acoustic impedance mismatch at the fruit-transducer boundary. The acoustic impedance of the transducer, Z_1, was taken to be 1.48 M Rayls.

Fig. 5 is superimposed with the theoretical reflection coefficient curve based on Eq. (1). The results show a high level of correlation between the theoretical and experimental values ($R = 0.858$).

The orange's density can be calculated from the reflection coefficient by Eqs. (1) and (2), hence giving an indication of water content. With this method, the technique can be reliably and non-destructively used to classify individual oranges based water content using regardless of individual physical factors such as size,

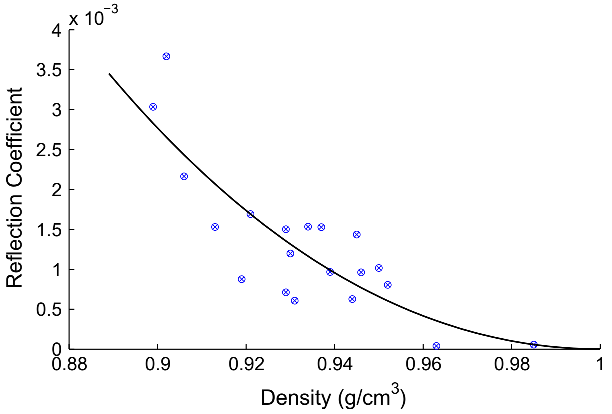

Fig. 5. Reflection coefficient for navel oranges, showing fit based on Eq. (1).

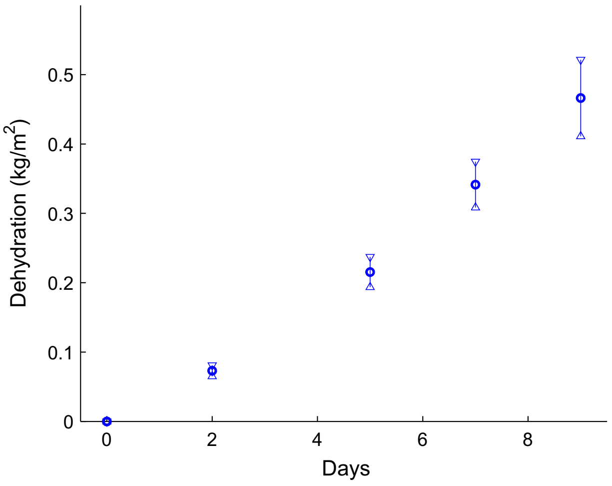

Fig. 6. Dehydration of navel oranges over time. Error bars show one standard deviation from the mean.

maturity and uniformity of the peel, allowing sub-standard oranges from within a single batch to be identified and discarded. The deviations from the theoretical case which do exist can largely be attributed to the physical state of the peel, as uniformity, smoothness and any imperfections will have an impact on the coupling between the transducer and the fruit.

5.3. Firmness and dehydration

Figs. 6–8 show measurements of dehydration, firmness and reflected ultrasonic energy respectively, taken on 75 navel oranges during a 9 day period, with 15 oranges being selected on each of the measurement days.

Over the 9 day period, dehydration of the oranges reached 0.47 kg/m^2. Dehydration appears to increase linearly, however it is expected that the results would reach a maximum where the oranges will no longer lose water content due to evaporation if the experiment were performed over a longer time period.

The force required to compress the oranges to 95% of their equatorial diameter decreases steadily from 23.5 N to 18.5 N as the fruit ripen over the first five days of the experiment, before beginning to plateau. The dispersion of the results decreases over the course of the experiment as the oranges begin with variances in maturity, but tend towards a final state. It should be noted that on the final day of the experiment, a number of the oranges were beginning to show signs of physical decomposition, which resulted in an increased dispersion of results on the ninth day.

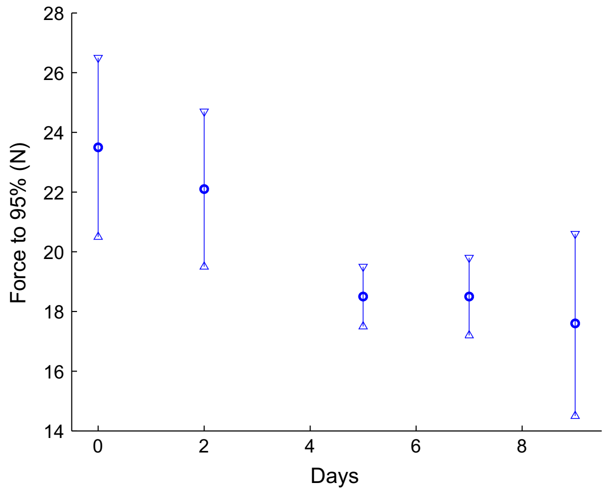

Fig. 7. Force required to compress navel oranges to 95% of their original equatorial diameter. Error bars show one standard deviation from the mean.

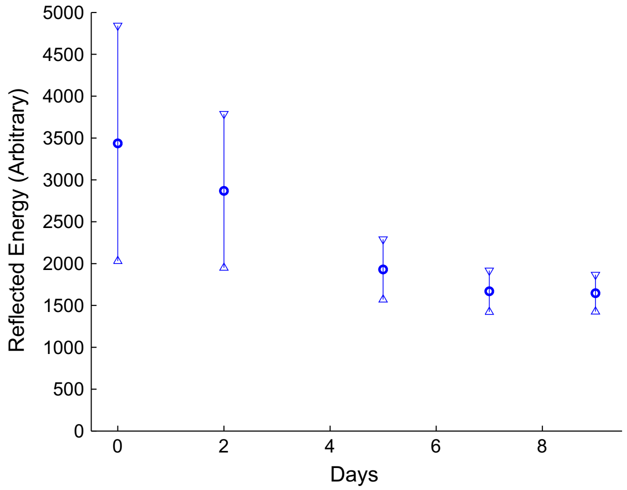

Fig. 8. Reflected energy for navel oranges over time. Error bars show one standard deviation from the mean.

Similarly, the level of reflected ultrasonic energy decreases for the first five days of the experiment before beginning to settle towards a final value. At the same time, the dispersion of the results decreases as the physical characteristics of the oranges converge. The ultrasonic results were not affected by any physical decomposition as the results rely only on the state of the peel rather than the physical structure of the entire fruit.

Table 1 shows the correlation between the physical and ultrasonic measurements, as well as time.

The reflected energy and firmness show the highest correlation ($R = 0.989$). As the oranges mature post-harvest their physical structure weakens, leading to a loss of firmness. With the transducer applied at a constant force, the loss of firmness results in improved coupling between the transducer and the fruit. This effectively decreases the second term of Eq. (3) as the quality of the dry coupling environment is improved with decreasing firmness. This relationship allows the ripeness of the oranges to be tracked nondestructively using the developed ultrasonic technique.

A strong correlation ($R = -0.960$) exists between dehydration and elapsed time, however if the experiment was continued over a longer time period, the dehydration should not be expected to

Table 1
Correlation coefficients (R) matrix for measured values.

	Reflected energy	Dehydration (kg/m^2)	Firmness (*N* to 95%)	Time (days)
Reflected energy	1.000	−0.892	0.989	−0.960
Dehydration (kg/m^2)	−0.892	1.000	−0.903	0.976
Firmness (*N*–95%)	0.989	−0.903	1.000	−0.961
Time (days)	−0.960	0.976	−0.961	1.000

remain linear with time and the correlation between the two would decrease.

6. Conclusion

The novel pulse-echo ultrasound technique was successfully applied to navel oranges post-harvest to non-destructively determine fruit quality with a high level of accuracy.

Firstly, the density, and hence water content of the fruit can be accurately determined regardless of individual physical characteristics such as size, maturity and the uniformity of the peel by isolating the portion of the results which relate directly to the acoustic properties of the fruit. Using this technique, individual sub-standard fruit can be identified and discarded at the time of harvest or during processing in a storage facility, whereas traditional destructive methods can only be applied to a limited sample of a harvest.

Secondly, over a period of nine days, the firmness and dehydration of 75 navel oranges were measured and ultrasonic readings were taken. A high level of correlation was found between the firmness of the oranges and the quantity of reflected energy. The technique could be used to replace traditional destructive firmness testing techniques used in storage and distribution facilities to monitor fruit quality and ripeness, allowing tests to be performed *in situ* without having to destroy a fraction of the crop.

The results reflect the two primary physical attributes which impact the technique. The first shows a relationship between the reflected energy and the density, and hence acoustic impedance, of the oranges, illustrating the effect of having an acoustic impedance mismatch between the transducer and orange despite the use of dry coupling. Meanwhile, the second shows a strong correlation between the level of reflected energy and the firmness of the oranges, demonstrating the result of creating a more homogeneous coupling boundary as the oranges soften.

It is foreseeable that the developed technique could be applied to oranges pre-harvest, allowing fruit maturity to be monitored and the optimal time for harvest to be determined. Additionally, the method can potentially be applied to other fruit where firmness and water content are primary indicators of quality.

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