Ultrasonic technique for non-destructive quality evaluation of oranges

D.S. Morrison*, U.R. Abeyratne*

School of Information Technology and Electrical Engineering, The University of Queensland, St Lucia, Brisbane, Australia

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.

Keywords: fruit, ultrasound, quality evaluation, non-destructive

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; Pal-
lottino et al., 2011), and hydration (Camarenta and Martinez-Mora, 2006). Such meth-
ods 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 unsuc-
cessful 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 vege-
tables due to the high levels of attenuation. Methods which have been successful in
performing ultrasonic measurements on fruit have been generally limited to using cum-
bbersome 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 re-
flexive 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 trans-
mission method through orange peels, Camarenta and Martinez-Mora (2006) deter-
mined a relationship 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 Figure 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 9V 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 30V peak-to-peak square signal.

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 100kHz 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 30V 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 Figure 2.

![Figure 2: Impulse Response (top) and Frequency Response (bottom) of ultrasonic transducer](image)

From Figure 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 wa-
ter, with an acoustic impedance of 1.48MRayls.

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 devel-
oped specifically for analysis of fruit, which uses ultrasonic echoes close to the surface
of the fruit and from the transducer-fruit boundary itself to classify the overall proper-
ties 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:

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

(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 gen-
erated ultrasonic energy is conducted into the medium. Without coupling gel, micro-
scopic 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 with-
out 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 absorp-
tion) 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 ultra-
sonic signals internal to the fruit would be subjected to high levels of attenuation and
dispersion.

Figure 3 gives an example of the recorded ultrasound reflections from a navel or-
ange under dry coupling conditions, showing the initial impulse response of the trans-
ducer and subsequent reflections of ultrasonic energy.

![Figure 3](image_url)

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

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
Figure 3. The results are given as the ratio of 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 Figure 3.

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

\[
Z = \rho c \ [\text{Rayls}]
\]

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

\[
RE = G \left( \frac{Z_1 - \rho_2 c_2}{Z_1 + \rho_2 c_2} \right)^2 + C \ [\text{J/J}]
\]

where \( G \) is a unitless scaling factor introduced by the numerical integration and quan-
tisation of the signal, and \( C \) is represents the energy reflection due to the impedance
mismatch caused by the dry coupling environment. Both terms of Eq. 3 relate to phys-
ical 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 con-
forms 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 de-
creasing 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 un-
changed 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 to 96 mm average diameter), ages (0 to 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 de-
structive 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 or-
ange 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 calcu-
lated 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 con-
stant 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 Figure 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.
Using the recorded mass ($W$, in kg), the dehydration ($D$) (the loss of weight due to evaporation) was calculated by:

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

where $S$ is the surface area of the orange in $\text{m}^2$.

5. Results

5.1. Effect of Transducer Coupling Force

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

![Graph showing reflected energy against applied force](image)

Figure 4: Comparison of results for varying transducer coupling 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 Figure 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

Figure 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 ($\Gamma$) 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 1.48MRayls.

Figure 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 experi-
The orange’s density can be calculated from the reflection coefficient by Eqs. 1 & 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, 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

Figures 6, 7 and 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/m². 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...

Figure 5: Reflection coefficient for navel oranges, showing fit based on Eq. 1
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.

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 non-destructively 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 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.

### References


- Designed a custom, portable ultrasound device specifically for fruit analysis
- Developed a novel ultrasound technique analysing on near-surface echoes
- Able to identify firmness and hydration of oranges using ultrasonic technique