Studying Kiwifruit with Laser Ultrasound and Seismology Techniques

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STUDYING KIWIFRUIT WITH LASER ULTRASOUND AND SEISMOLOGY TECHNIQUES

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ABSTRACT

Elastic wave approaches are natural and promising candidates for fruit quality monitoring. Recently, we showed that viscoelastic properties of apples can be measured using laser-generated and laser-detected ultrasonic waves – a completely non-destructive and non-contacting method. Here, we discuss similar measurements on golden kiwifruit of varying quality. We find that our observations are repeatable and informative, can be used to monitor fruit ripening, and have the potential to distinguish between 'good' fruit and those with a tissue breakdown disorder.

1. INTRODUCTION

The elastic properties of fruit can be directly related to their quality, age, and composition [1–3]. Firmness is one of the most commonly-used fruit quality measures. The standard firmness test is the Magness–Taylor (MT) pressure test [4], in which the force required to deform the fruit is measured by pushing a small rod into the surface to the point of penetration. Other methods used to probe firmness or other elastic properties are also mostly destructive, including twisting [5], compressing [6, 7], or dropping fruit [8].

For non-destructive testing, optical absorption and scattering methods have been used to estimate fruit soluble solid content [9], texture [10, 11], and skin cellular structure [12]. Acoustic measurements have also been used to monitor a variety of types of fruit [13–17]. Acoustic resonance spectroscopy methods have shown that the vibrational characteristics of ellipsoid fruit can give a direct estimate of firmness [18–20]. Recently, we introduced a completely non-destructive and non-contact method of detecting elastic waves in apples – an approach which avoids the contact issues encountered in most acoustic techniques. Using this method, we showed that quantities such as the elastic modulus and Poissons ratio can be measured [3].

Here, we present a similar approach to characterizing golden kiwifruit. Kiwifruit are often stored for long periods before shipping. While in cold storage, kiwifruit can develop a disorder in which their structure breaks down, beginning with the inner surface and progressing to the core (Fig. 1). This disorder results in areas of both granular and soaked tissue. As kiwifruit are Aotearoa New Zealand's largest industrial export [21], a simple, non-invasive way to detect such disorders would be invaluable for industrial quality monitoring.

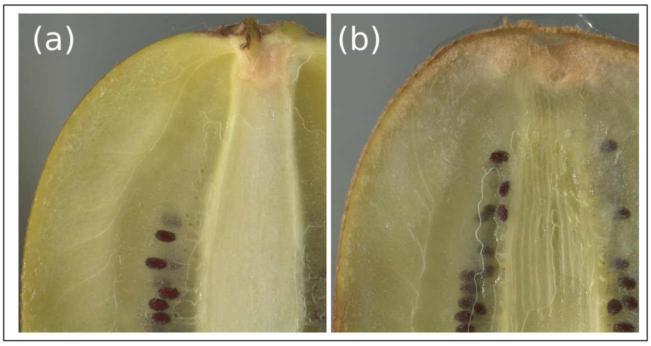

Figure 1. Representative examples of kiwifruit (a) without and (b) with storage breakdown disorder.

Our experimental setup involves rapid scanning of a laser Doppler vibrometer detection point around the equator of the kiwifruit. To our knowledge, the measurements presented here constitute the first observations of elastic waves in kiwifruit. Interestingly, these datasets of elastic waves in ellipsoid fruit can be seen as directly analogous to those obtained in seismology. Both surface and body waves can be observed and their velocities and absorption measured. We are able to use absorption values to distinguish between fruit of differing quality, even when such differences are not evident from the fruit's exterior. Here, we discuss this rich set of information obtained from simple, non-contact measurements on kiwifruit.

2. METHODS

A high-powered pulsed laser is aimed at one side of the kiwifruit to excite an ultrasonic waveform in the fruit via non-destructive thermoelastic expansion. On the opposite side of the kiwifruit, a laser Doppler vibrometer measures any displacement of the surface of the fruit (Fig. 2a). The vibrometer is rotated around the equator of the kiwifruit to measure the surface displacement at points around the fruit. Reflective tape is applied along the fruit equator to optimize the amount of reflected light incident at the detection interferometer.

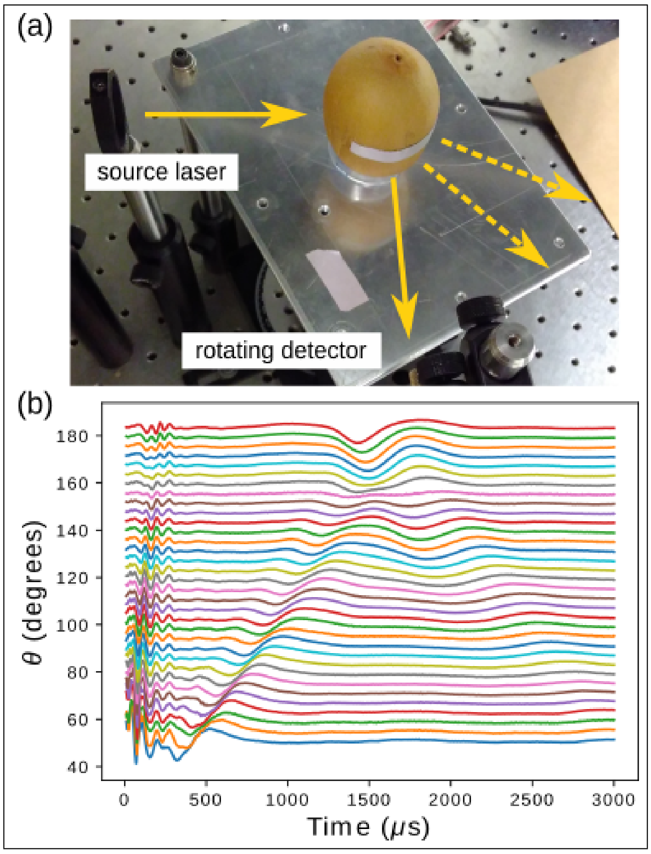

Figure 2. (a) Setup for LUS measurements on kiwifruit, in which the detector is rotated around the equator of the kiwi. (b) Example of data recorded with rotating detector setup. Plotted is the amplitude of transmitted waves as a function of angle between source and detector. In this plot, two waves can be seen: the P-wave at early times, and R-waves at later times.

Representative measurements from this setup are shown in the *wiggle plot* of Fig. 2b – a common figure style in seismology. Two types of waves can be seen by eye: (1) the *P-wave* ($0 - 250\mu$s) – the pressure or body wave which travels straight through the fruit with group velocity v_P, and (2) the *Rayleigh waves*, or R-waves, which travel around the surface of the fruit with group velocity v_R ($500 - 3000\mu$s). In Fig. 2b, R-waves arriving at $\theta = 180°$ have travelled around the fruit circumference in opposite directions.

3. RESULTS AND DISCUSSION

To test the relevance of elastic wave propagation for probing kiwifruit quality, we performed preliminary time-lapse measurements at $\theta = 180°$, as the fruit ripened. The measurements were made on the same kiwifruit twice per day over five days, and the average firmness of ten other control fruit monitored with two destructive methods: using a penetrometer, and a rebound test which measures the effect of a small tap on the surface of the fruit. Results are shown in Fig. 3. The P-wave velocity was found to decrease with ripening (firmness), which could be caused by a decrease in Bulk modulus. The amplitude of the transmitted P-waves was also found to diminish as the fruit ripened, and seems to be more sensitive than arrival time to a decrease in firmness, especially early on in the process (1–3 days).

We also report on measurements made on a range of fruit which suffer from severe, mild or no breakdown disorder. No fruit shows any sign of disorder from the outside. All fruit weigh between 116 – 126 grams, have lengths of around 6.8 – 7.4 cm, and diameters of 5 – 5.3 cm. After acoustic measurements were performed, the firmness of each fruit was measured and disorder severity was estimated. Firmness was measured with a penetrometer after acoustic measurements were performed (averaged over two readings taken on the equator of the fruit). Estimates of disorder severity are shown in Table 1, evaluated by eye from the insides of the fruit (Fig. 1).

Firmness (kgf)	Disorder severity	ℓ_a^P (cm)	ℓ_a^R (cm)	v_P (m/s)	v_R (m/s)
0.43	2	8.5	12	120	3.8
0.21	2	14	8	140	2.8
0.26	2	5.0	8	140	3.7
0.42	1	15	16	92	4.5
0.47	1	5.0	22	105	3.9
0.40	0	20	15	92	3.4
0.22	0	15	15	134	3.7
0.26	0	25	17	75	3.7

Table 1. Measured properties of kiwifruit: firmness, density (ρ), breakdown disorder severity ranging from 0 for none to 2 for severe, and absorption lengths and group velocities of P-wave (P) and R-waves (R), respectively.

The relative amplitude of the transmitted P- and R-waves at different detector points gives a measure of the energy loss of the waves as they travel through the fruit. This loss can be quantified using the extinction length, ℓ_{ext}. ℓ_{ext} describes how far into a material a wave travels without there being a high probability that it has been either absorbed (ℓ_a) or scattered (ℓ_s), and can be written as $1/\ell_{ext} = 1/\ell_a + 1/\ell_s$. Here, we can expect the contribution of scattering to be negligible next to that of absorption ($\ell_a \gg \ell_s$) [3]; the wavelengths that we use to probe the kiwifruit are larger than the detail of the inner fruit structure (P-waves correspond to frequencies of approximately $f \sim 2 - 5$ kHz, R-waves to $f \sim 10 - 20$ kHz). Thus, we make the approximation that $\ell_{ext} \approx \ell_a$. We estimate the effect of absorption of both P-waves and R-waves (denoted ℓ_a^P and ℓ_a^R, respectively) by plotting the peak transmitted intensity T as a function of distance d travelled inside the kiwifruit; T should decrease with distance as $T \propto \exp(-d/\ell_a)$. Similarly, P-wave and R-wave velocities can be measured by fitting a straight line to a plot of source-receiver distance through the fruit versus peak arrival time (Fig. 4). Results are summarized in Table 1.

We observe that the acoustic properties of fruit which may be sensitive to the presence of breakdown disorder are

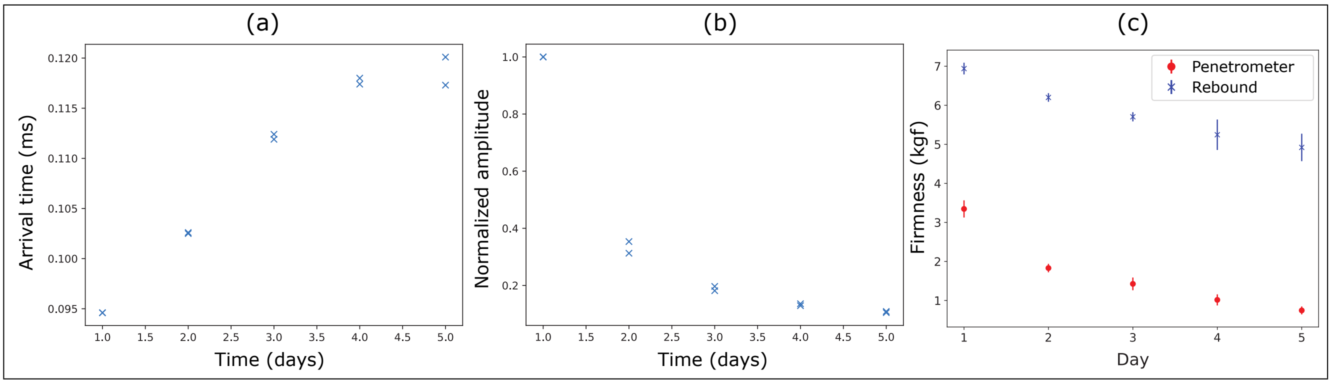

Figure 3. (a) The arrival time of the maximum of the waveform at $\theta = 180°$, as a function of relative kiwifruit age. (b) The maximum amplitude of the waveform at $\theta = 180°$ as a function of relative kiwifruit age. (c) Although absolute values of the mechanical tests vary, both show a decay in firmness as the kiwifruit ripens.

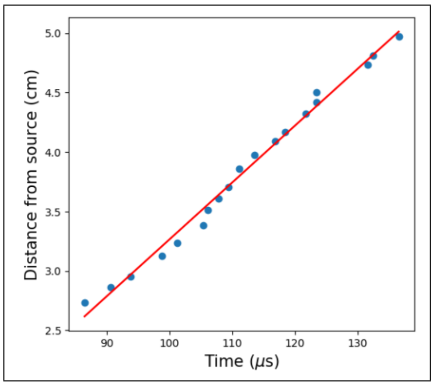

Figure 4. Representation of the estimation of P-wave velocity in a kiwifruit. Plotted is source-detector distance d (straight through the fruit) versus travel time t of the P-wave between those points. Velocity v_P is found via the slope of a straight line fit: $v_P = d/t$.

also sensitive to firmness. P-wave and R-wave absorption lengths are lower in kiwifruit suffering from storage disorder than in those without; however, the same could also be said for softer versus firmer fruit. P-wave velocity seems to be higher in kiwifruit with the disorder than in those without – the opposite effect that might be expected for soft versus firm fruit. Further study of both storage disorder and ripeness is required to separate these two effects with confidence. Further studies will also examine the possible influence of scattering (ℓ_s); it is possible that the increases in v_P are related to structural changes resulting from the storage disorder.

4. CONCLUSION

We can confirm that the relative ripeness of kiwifruit can be monitored with laser ultrasound (LUS) measurements. This behaviour may seem unsurprising, and agrees with studies of other fruit such as apples [3], mangos [22] and avocadoes [23] which have found that the velocity of acoustic body waves decreases as fruit ripens and softens; however, this relationship does not seem to hold for all types of fruit [22], and was thus important to verify here. We also observe that absorption (transmitted acoustic amplitude) is more sensitive than v_P to firmness, especially earlier on in the ripening process.

Finally, we have shown that laser ultrasound measurements on kiwifruit can be used to differentiate fruit with storage breakdown disorder from those without, especially for firm fruit. This study shows that, while acoustic measurements are extremely sensitive to both breakdown disorder and firmness/ripeness, these effects are not easily separated. To quantify the severity of breakdown disorder therefore, further studies will be limited to firmer fruit.

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