Non-contact Assessment of Apple Condition using Magnetic Induction Spectroscopy: Preliminary Results and Indications

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***Abstract*—Bioimpedance spectroscopy is the electrical impedance of a biological sample measured over a range of different frequencies. Over the kHz to MHz range, the characteristic shape of the spectra is denoted as the β dispersion, and is the result of the polarisation of cell boundaries presenting a *capacitance* that contributes to the overall flow of electrical current in the sample. This implies that the curve of the dispersion could be a marker for breakdown behaviours and cell vitality within the fruit, as variations in the cell walls (looseness or cell death) will present different overall capacitances.**

In this paper, we present some early results exploring the relation between the bioimpedance spectra and variations in the fruit quality of apples, caused by different growing conditions, irrigation, stress, and injury. We use a novel measurement technology termed *Magnetic Induction Spectroscopy* which uses magnetic fields and induced eddy-currents to ascertain a relative conductivity measure over a frequency range from 50 kHz to 2.5 MHz. The significant advantage of this approach is that it is non-contact, opening the possibility of future in-field or process-line operation.

***Index Terms*—bioimpedance, magnetic induction, food quality, non-destructive testing, eddy-currents**

I. Introduction

Bioimpedance spectroscopy is the measurement of electrical impedance of a biological sample over a specified frequency range. Properties measured include conductivity, permittivity, and resistance of the sample amongst others. These properties, measured in bulk form across the sample, feature a characteristic frequency dependence caused by the non-homogenous physical structure of the tissue. A typical bioimpedance spectral profile is shown in figure 1. Conductivity generally increases, and permittivity decreases, in a series of broad step-like curves referred to as dispersions.

There are three dispersions commonly identified, classified as α, β, and γ [2], with each dispersion caused by the different electric field and electric current transmission mechanisms transitioning and becoming dominant within the sample at different frequencies. For instance, the α dispersion is the result of ionic diffusion across cell membranes and is dominant at the lowest frequencies (few hundred Hertz), whereas at the opposite side of the spectra, the γ dispersion is a result of molecular dipole relaxations occurring over the microwave range.

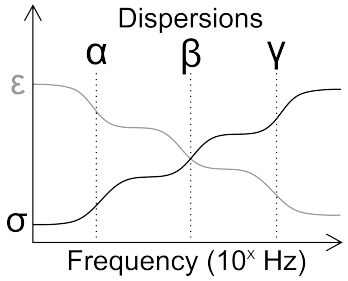

Fig. 1. Bioimpedance spectra and dispersion regions from low Hertz to Microwave

In what follows, we will explore the link between the bioimpedance spectra and the properties of fruit - specifically apples - that relate to produce quality. For this, we are most interested in the β dispersion - a product of the polarisation at the cell boundaries presenting a capacitance to electrical current flowing in the sample. At low frequencies, the cell boundaries present a high impedance and current will flow around the cells through the resistive extra-cellular fluids. At higher frequencies, the charging and discharging of cell boundaries presents a lower-impedance which overall, appears as a bulk increase in conductivity across the sample.

It is supposed that the β-dispersion of fruit could be a good indicator of its internal condition, premised on the fact that

the cell membrane capacitances will change as the cells loosen or break down with fruit ripening or injury. For example, this has been observed for ripening behaviour in a range of fruits - from nectarines, persimmon fruit, garut citrus and mangos [5], amongst others. Damage and bruising has been explored and shown to induce changes in the β dispersion characteristics [3], [4] even immediately after the bruising impact event before the bruise is visible. How to translate this work into a means of bruise detection and measurement however, is still an open question.

We propose to measure the bioimpedance spectra of apples using a technique referred to as *Magnetic Induction Spectroscopy* (MIS). Most studies of bioimpedance use direct contact electrodes - metal probes inserted in to the fruit or secured to the surface - to couple electric-current in to the sample and measure resultant potential differences. However, the use of electrodes can be problematic. For instance, insertion of the electrodes is destructive to the fruit, while the electrode-tissue interface can feature complex frequency dependent impedances and be prone to measurement artefacts [5].

MIS by contrast is a non-contact approach. A typical MIS arrangement consists of an excitation coil, receive coil and reference coil. The excitation coil is driven by an oscillating current to generate an oscillating magnetic field. The sample is illuminated by this field, inducing eddy currents within the sample, that in turn induce a secondary magnetic field measured by the receive coil. By comparison of the excitation magnetic field measured by a reference coil, and the secondary magnetic field measured by the receive coil, we can determine conductivity and permittivity from the following relation [5], [6],

$$\frac{V'(\omega)}{V_{rf}(\omega)} = P\mu_0\omega(\epsilon\omega - j\sigma) \tag{1}$$

where $V_{rx}(\omega)$ is the complex frequency component of the voltage measured by the receive coil with the background or voltage induced by the excitation field subtracted. $V_{rf}(\omega)$ is the voltage measured in the reference coil. The term ω is frequency (rads/s), μ_0 the permeability of free-space, ϵ the permittivity of the sample, σ the conductivity, P is a geometric constant, and $j = \sqrt{-1}$. In what follows, we use conductivity only and emit the component containing permittivity. One of the challenges with MIS is determining P which is specific to the geometry of the coil arrangement and the shape and size of the sample. Unless the coil-sample geometry is consistent across the batch, then it is difficult to calibrate and find a solution for P that is suitable for each sample. We therefore introduce the term *relative conductivity* which is the product of the geometric factor P and the conductivity ($\hat{\sigma} = P\sigma$).

In this paper, we investigate the bioimpedance spectra of apples from orchards under different irrigation and growing conditions that yield different quality grades of fruit. Bioimpedance is presented in the form of relative conductivity across a frequency range from 50 kHz to 2.5 MHz and is measured using a new MIS measurement system previously described in [1]. We explore whether the relative conductivity spectra is associated with the quality grades, and whether the spectra compares to the degree of bruising for different apples, measured from apple cross-sections across the midline using a semi-automated image processing algorithm.

II. Method

Samples are measured using the magnetic induction spectroscopy system introduced in [1], shown in figure 2, and following the calibration procedures reported in the same reference. Each sample was measured for approximately 1 minute. Background (empty) measurements were taken between each sample scan, and two calibration measurements were taken at the beginning and end of each batch using (1) a 125ml bottle of saline ($\tilde{0}$.7 S/m), and (2) a small ferrite piece. These objects calibrate respectively for magnitude - normalising to fixed conductivity saline - and phase - rotating to the known phase response of a low conductivity high permeability ferrite.

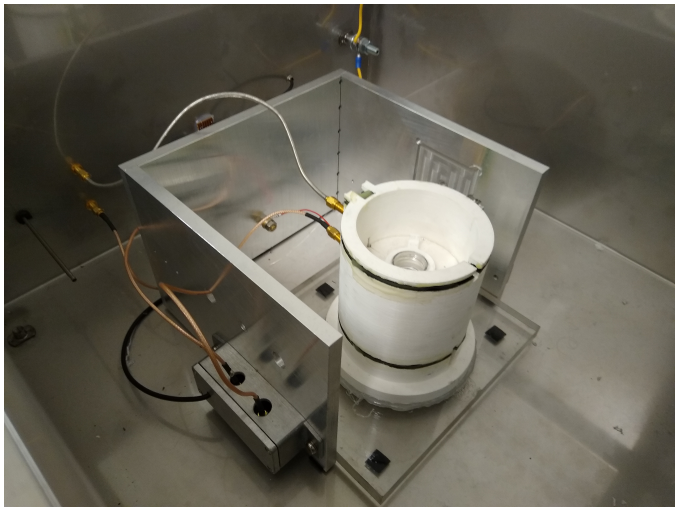

Fig. 2. Magnetic induction spectroscopy system.

A total of 63 Braeburn apples were scanned across four different batches. Braeburn is a variety naturally prone to internal breakdown of the flesh caused by poor gas porosity properties leading to localised anaerobic conditions caused by depleted O_2 and elevated CO_2 concentrations.

The batches were as follows:

- BP: 15 apples pre-stressed by storing fruit in 2% CO_2 gas for 4 months.
- W: 16 apples from an orchard producing low internal quality fruit.
- H23: 16 apples from an orchard producing apples with intermediate internal quality fruit.
- H21: 16 apples from an orchard producing good quality fruit with no signs of internal breakdown.

After an apple is scanned, it is cut across the mid-line to expose the inner flesh and internal bruising. The extent of bruising is measured as a proportion of the cross-sectional area of the apple. The area of the bruised flesh is measured using

an image processing algorithm developed using the openCV library [8]. The algorithm requests that the user select a region of interest (ROI) from the image, which is then used to build a cluster of Red, Green, Blue (RGB) values. The other pixels in the image are then assigned as belonging to this cluster or not depending on the Mahalonbis distance. This algorithm is used to first remove the background (by selecting a background ROI) and then to identify bruised flesh by selecting healthy apple tissue as ROI. The residual apple-core in the cases when it is not removed by the background selection is removed manually. A sample image and identified bruise region is shown in figure 3.

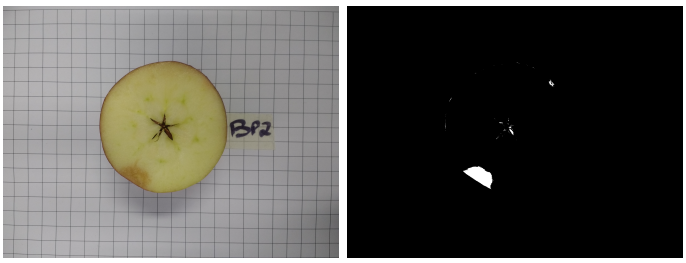

Fig. 3. Apple cross-section and identified bruised region.

III. Results and Discussion

The relative conductivity spectra for two typical apples are shown in figure 4, with one apple selected from the high quality group and the second from the CO_2 stressed group. We can observe a clear curve indicative of the β dispersion. The curve appears to flatten at higher frequencies but not at the lower frequencies. This suggests our frequency bandwidth is not capturing the full-dispersion but rather the upper region.

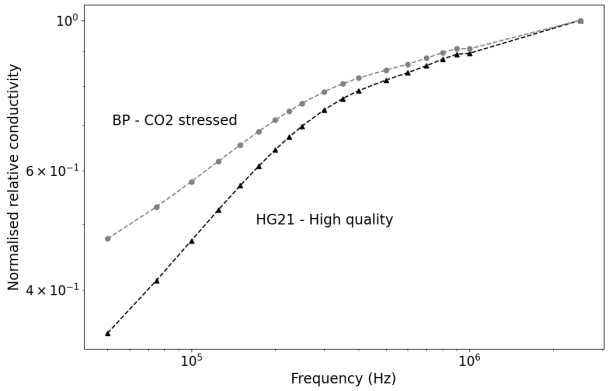

Fig. 4. Bioimpedance curves.

The gradient or steepness of the curves at the lower frequencies is distinctly different between the two samples, with the stressed apple showing a flatter response. This supports our premise that the cell capacitances can be inferred from the dispersion curve. We would expect a stressed fruit, where cell walls may have been degraded, to exhibit a flatter response. Indeed, we have previously shown this in the extreme case by freezing and thawing the sample to destroy cell structures. The result is an almost uniform or completely flat spectra across the same frequency range.

To extend our analysis to the full sample set, we will define two terms to capture the characteristics of the dispersion curves:

1) Gradient $d\hat{\sigma}/df$ at 200 kHz: That is the rate of change of the spectra with respect to frequency at the 200 kHz point. The gradient is calculated using a local polynomial fit to the curve which is then differentiated with respect to frequency.
2) P_y parameter [7]: This is a normalised ratio that uses a high frequency component, minimally affected by cell capacitances, to normalise a low frequency component in order to reduce dependency on sample size and shape. The parameter in our case is given by the following,

$$P_y = \frac{\hat{\sigma}(1MHz) - \hat{\sigma}(100kHz)}{\hat{\sigma}(1MHz)}$$

The choice of gradient at 200 kHz is abritary, justified by the observation that the dispersion curves of the apple are relatively linear around this frequency, that lower-frequencies are generally more affected by changes in cell capacitances (cell wall loosening, etc), but that the very lowest frequencies (50 kHz, 100 kHz) suffer more from lower signal-to-noise. The P_y parameter is a simple and established method for characterising the dispersion curves. Other common methods that incorporate the full curve include matching to equivalent circuits to obtain physically relevant electrical properties (cell wall capacitance, ionic conductivity of intra/extra-cellular fluids, etc) [9]. This is beyond the scope of our current work.

Figure 5 shows a box plot of the gradient at 200 kHz for each apple batch. We note a number of outliers for this parameter, possibly due to poor curve fits or outlier frequencies. Nevertheless, a number of results emerge: Firstly, the means for each batch descend in order of quality, indicative of a flattening of the dispersion as quality diminishes. The highest quality batch (H21) is distinctly different from the stressed batch (BP) although with some overlap. The distinction between high, intermediate (H23) and low (W) quality batches are much less clear.

Figure 6 shows a similar result for the P_y parameter. The high quality H21 batch is distinctly different from the stressed BP batch and more distinct from the low W and intermediate H23 batches than the gradient result. However, we note the reversal of order between H23 and W which may indicate that these groups cannot be distinguished and the ordering may be random.

A T-test is used to establish the statistical significance of the difference between the batches. The probability values (p-numbers) are shown in table I. These results confirm our evaluation of the box plots. For the gradient method, only the difference between H21 and BP is statistically significant with a threshold $p < 0.05$. The batches W and H23 show a high probability of a shared mean indicating that these batches are

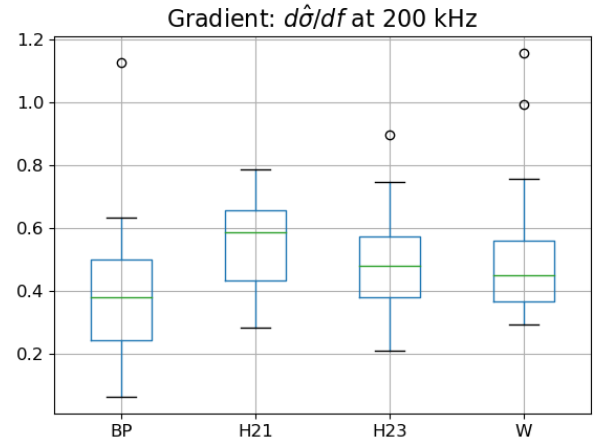

Fig. 5. Box plot showing the gradient $d\hat{\sigma}/df$ at 200 kHz for each apple batch

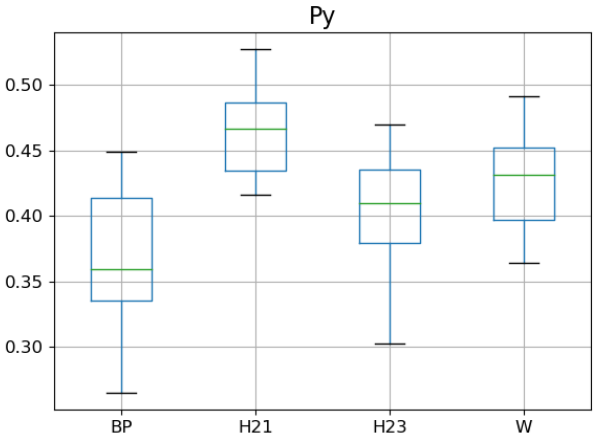

Fig. 6. Box plot showing the Py parameter for each apple batch

not easily distinguishable. Note that the outliers shown in the figure 5 were removed to preserve the assumptions of the test. The results for P_y showed a clearer differentiation. Both the high quality H21 and stressed BP batches have statistically significantly different means to the all the others. Only W and H23 did not meet the $p < 0.05$ threshold. No outliers were removed for the P_y test.

TABLE I
T-TEST P-VALUES: PROBABILITY THAT TWO GROUPS SHARE THE SAME POPULATION MEAN.

$d\hat{\sigma}/df$ at (200 kHz)			
	BP	W	H23
BP	-	0.122	0.077
W	-	-	0.75
H21	0.003	0.065	0.128

P_y			
	BP	W	H23
BP	-	0.001	0.049
W	-	-	0.114
H21	0.000	0.002	0.000

We complete our analysis by determining the Pearson correlation coefficients of the gradient and P_y parameter. Magnetic induction measurements are known to have dependency on the size and shape of the sample. We therefore explore the correlation with mass and average diameter of the fruit to determine if the geometry dependency is diminished. We also explore the correlation with bruising using the bruise measurements established by our image processing algorithm.

The correlation coefficients are shown in table II. In addition to gradient and P_y, we also include a single frequency relative conductivity result (at 200 kHz) for comparison. Clearly for both diameter and mass, the single frequency measurement shows a higher correlation (0.663, 0.675). This is reduced for both gradient and P_y. The latter appears particularly effective at compensating for the sample geometry.

TABLE II
PEARSON CORRELATION COEFFICIENTS.

Characteristic	$\hat{\sigma}$(200 kHz)	$d\hat{\sigma}/df$	P_y
Mass	0.663	0.436	-0.145
Diameter	0.675	0.434	-0.129
Proportion Bruising	0.102	0.173	0.015

The average apple mass was 168.2 g with a range from 104 g to 271 g. The average diameter was 68.9 mm with a range from 58.2 mm to 80.5mm.

The correlation between bruise proportion and the three parameters is poor in each case. This is a somewhat surprising result given earlier results that we can gauge apple stress from the bioimpedance curves. We would expect some link to damaged apple flesh in line with prior research in the literature such as [4]. This result might indicate a lack of sensitivity to the bruise. The proportion of bruise to cross-sectional area was less than 5% in each case and it is possible any changes to the dispersion curve for bulk measurements of the apple were within the instrument noise. A more focused measurement, sensitive to a region rather than the bulk, may yield better results. For example, [4] used electrodes across the bruise site.

We must also consider the accuracy of our image processing algorithm. The algorithm generally performed well with the distinctive bruises forming near the skin of the apple. However, the algorithm was poor at capturing the regions of internal breakdown, i.e. the greying flesh closer to the core as shown in figure 3. In many apples this internal breakdown, rather than bruising on the apple periphery, was more signifiant and we suspect had an impact on the bioimpedance curves. An improved algorithm is necessary to capture this flesh characteristic, possibly aided with staining techniques.

IV. CONCLUSION

We have shown that magnetic induction spectroscopy can effectively measure the upper portion of the bioimpedance β dispersion curve for apples, at least in the form of relative conductivity. We have also shown that using the characteristics curve, we can establish to a limited degree the difference between apples from across different quality groups. This was especially true of apples which had received an injury by CO_2 gas treatment. What is less clear is the relation between the

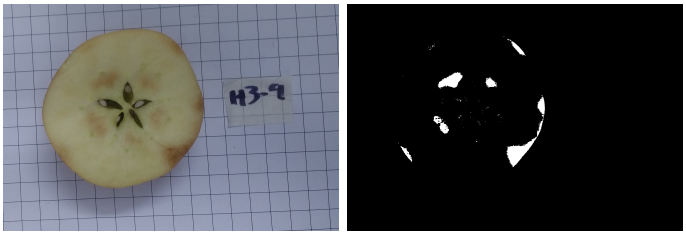

Fig. 7. Serious internal flesh breakdown in apple (left) which has not been fully captured by the bruise detection algorithm (right).

shape of the β dispersion measured in bulk across the whole apple, and presence of localised damaged flesh in the form of bruising. In this case, we were not able to achieve a correlation, in contrast to previous work in the literature.

Bioimpedance spectroscopy in general is known to correlate with several characteristics of plant and fruit health, not least the results in the present work. If these correlations can be harnessed to create predictive tools, then this approach has considerable potential as a monitoring and diagnostic technique for food production. It may prove particularity important in the growth of precision agriculture as we attempt to respond to the threat of climate change and water shortages. For example, Caravia et al. [10] found correlations between bioimpedance and loss of cell vitality in Shiraz berrys due to high temperatures and water stress in growing conditions.

The utility of bioimpedance spectroscopy is further multiplied by using measurement techniques such as MIS. As a non-destructive, non-contact approach, MIS projects opportunities for using bioimpedance spectrosocpy across a range of applications in food production, from on-the-vine farmyard assessment to end-user retail and quality control. Future work will consider more sensitive and more localised approaches to induction measurement as we seek to realise the potential benefits of MIS as a practical non-contact method of measurement.

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