Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/issn/15375110

Research Paper

Detection of internal defects in onion bulbs by means of single-point and scanning laser Doppler vibrometry

Sandra Landahl, Leon A. Terry *

Plant Science Laboratory, Cranfield University, Bedfordshire, MK43 0AL, UK

ARTICLE INFO

Article history:
Received 24 November 2021
Received in revised form
30 June 2022
Accepted 6 July 2022

Keywords:
Allium cepa
Botrytis allii
Sprouting
Rot
Grading

The number of onion consignments which are rejected or downgraded due to the incidence of internal defects is a continuing problem for wholesalers and growers. Defects may only be up to 4% incidence level, but result in the entire lot being lost for sale. Destructive quality control testing causes waste, so that there is a need for alternative non-invasive assessment. The aim of the current research was to demonstrate whether internal defects could be detected using Laser Doppler vibrometry (LDV). Several trials, with different types of sensors and levels of onion defect severity were conducted. Both scanning and single-point LDV were employed in order to develop a suitable measurement method to evaluate onion defects. It was necessary to measure resonant frequency at the neck or equator of the bulbs in order to segregate neck rot (*Botrytis allii*) or bacterial rot, respectively, but LDV could not differentiate sprouting and double hearted bulbs from sound onions. In conclusion, it was possible to non-destructively identify onion bulbs with only a 5% area affected with neck rot (visible after cutting). It would be necessary to calibrate for different onion cultivars and origins, if the technique is to be implemented on a commercial sorting line.

© 2022 The Authors. Published by Elsevier Ltd on behalf of IAgrE. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

1. Introduction

Many onion lots are rejected or downgraded due to the incidence of internal defects. Even though defects may typically only occur in 4% of harvested onions, they would still result in the entire batch being unacceptable for retail sale. Internal defects in onion can be either physiological (premature sprouting) or pathological, principally caused by endophytic bacteria (e.g. *Pseudomonas* spp. and others) and fungi (*Botrytis allii*). The UK onion industry estimates, over 10,000 tonnes of onions annually could be saved with a value of ca. £4 million, which are rejected due to a small percentage of infected bulbs per batch, if grading could be enhanced; non-destructive grading could eliminate cost incurred by manually cutting and therefore loosing 2000 tonnes onions per annum (Technology Strategy Board project TP320-257).

Several non-destructive techniques, such as near-infrared reflectance (NIR), magnetic resonance imaging and X-ray imaging exist for detecting internal decay or mechanical damage in fresh produce (Kamal et al., 2019). In addition, machine vision systems are being developed for phenotyping in the field (Kim et al., 2018 and 2020). Indeed, a combined model for

* *Corresponding author.*
E-mail address: l.a.terry@cranfield.ac.uk (L.A. Terry).
https://doi.org/10.1016/j.biosystemseng.2022.07.004
1537-5110/© 2022 The Authors. Published by Elsevier Ltd on behalf of IAgrE. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

NIR rot-detection (*Pseudomonas* sp.) and threshold optimisation approach has been shown to decrease the loss of sound bulbs, but temperature dependence and positioning of the light source and onion bulbs towards the detector remain challenging (Nishino et al., 2019). The onion bulb consists of concentric layers (laminae) emanating from the basal plate and culminating in the neck. Moreover, it was demonstrated that internal defects could be identified in onion bulbs using X-ray imaging to reduce defective bulbs per box by up to 95% (Mosqueda et al., 2010; Wang & Li, 2015). However, in order to make the installation of X-ray technology economically sustainable a price-premium grade category would be necessary. The challenge remains, therefore, to develop non-invasive technologies, which can evaluate internal onion quality at a sufficiently rapid speed and resolution to make it commercially viable.

Laser Doppler vibrometry (LDV) has been shown to be applicable for measuring avocado fruit firmness (Landahl & Terry, 2020), but there is no information on its potential to detect internal defects in fruit and vegetables. LDV is a non-destructive technology sensing the frequency shift of back scattered light from a moving surface based on the Doppler-effect. Resonant frequency (RF) of an object depends on many parameters (e.g. mass, stiffness, shape). In a simple harmonic motion the values stiffness and mass characterise a harmonic oscillator and determine its frequency. Damping is the attenuation of the vibration or in different words the energy dissipation in a volume of (viscous) media. Partially decayed laminae are structurally different and less dense compared to adjacent laminae and thus should respond with different vibration due to damping. In visco-elastic media like fruit and vegetables, stiffness and damping tend not to correlate. Understanding structural changes that are associated with internal defects will provide a foundation for objective and non-destructive assessment of postharvest bulb quality.

The research presented herein centred on differentiating onion bulbs with internal defects, firstly by using scanning LDV and then single-point LDV. Scanning LDV allows mapping of vibrations over a surface. A programmed pattern of points is measured successively, while repeated vibration actuations are provided. It offers vital information on the vibration mode of the object and through interpreting this, it becomes possible to localise the best position of where to direct single-point measurements, in order to measure a change in the vibration caused by physiological or physical changes of the object. Scanning LDV is different to finite element modelling, since it measures real values. The application of scanning LDV on horticultural produce is a novel approach, previously prohibitive due to its high acquisition cost. In contrast, single-point LDV is more suitable for an industrial environment, since it is quicker (less points to measure) and cheaper (requires a simpler sensor head) than scanning LDV.

The aim of the study was investigate the feasibility to reduce wastage by identifying and then automatically rejecting onions with an unacceptable level of internal defect at sufficient speed to be applicable on a grading line. The objectives of the presented work were to demonstrate proof of concept that RFs obtained through LDV are associated with internal defects and that algorithms to evaluate and measure these features can be created.

2. Materials & methods

2.1. Materials

See Table 1.

2.2. Methods

2.2.1. Defect assessments (destructive)

Quasi-static stiffness was measured as the force required to compress the whole bulb in the equator region using a 30 mm diameter plate and parallel fixed platform coupled to a uniaxial testing machine (model 5542, Bluehill© software v2. Instron, Norwood, MA, USA) at a speed of 50 mm s^{-1}. Load at 3 mm and slope of the force-deformation between 1 mm and 2 mm were recorded.

Each bulb was cut longitudinally and photographed. A subjective severity scale was introduced for visual inspection of the photos, in order to describe the bulbs' magnitude of defect (see Appendix 1, Fig. A1). The scale's threshold values were chosen as, 0: corresponding to no visible infection, 1: up to 5% rot, 2: up to 10% rot, 3: up to 25% rot, 4: more than 25% rot on the cut surface area (photo key in supplement).

2.2.2. Inoculation with Botrytis allii to cause neck rot

To prepare the inoculum, briefly, purchased *B. allii* isolate (CABI, UK) was grown on potato dextrose agar with 1 g l^{-1} streptomycin in Petri dishes according to supplier instructions: the agar was incubated at 22 °C with 12 h light/dark cycle. Then conidia were harvested, by flooding plates with 2 ml sterile water containing Tween 80 (Sigma, UK) and the conidia were dislodged from the hyphae with the aid of a sterile glass spreader. The resulting conidium solution was divided into three replicates, each of which were subsequently diluted to a stock with sterile water.

For cultivars SS1 and Elk: bulbs were inoculated with (±) *B. allii* (IMI # 292066, the causal pathogen of neck rot disease). Each lot of inoculated and control onions consisted of 3 groups with 3 replicates. Conidium solution at a concentration of 50,000 cfu ml^{-1} or sterile water, 100 μl respectively, were pipetted onto the cut neck of onion bulbs. This cut was made with a sterile blade across the mostly dry neck to reveal a small amount of fresh onion tissue. Onions were left to air dry for 30 min then returned to storage.

For cultivars Centro, Arthur and Setton five treatments were applied, *viz* control and four conidium solutions with different strains of *B. allii* (IMI42078, IMI147186, IMI292066 and a proprietary strain from Syngenta Seeds Ltd., UK) at 30,000 cfu ml^{-1}, respectively. Onion skin was disinfected with 70% iso-propanol solution before ca. 100 μl inoculum was injected by 1 ml Luer Lock syringe fitted with a 23G needle (BD3007000, BD Microlance, Switzerland) near the neck of the bulbs. The puncture aimed at a depth close to the centre of the neck. Occasionally small amounts of inoculum leaked out of the puncture. Needles were changed every 10 samples. The control bulbs were not punctured.

2.2.3. Scanning laser Doppler vibrometry

In the experiments utilising the scanning LDV (PSV-400 scanning head, OFV-5000 Vibrometer Controller, PSV-E-401 Junction Box, VIB-A-T02 Tripod, Polytec Ltd., UK) the bulbs were excited by a shaker (LDS V201, Ling Dynamic Systems Ltd., driven by function generator TG300, TTi) with a periodic chirp from 450 Hz to 2000 Hz. A small glass Petri dish was rigidly attached to the shaker pin (by means of superglue). The dish had a circular shaped inner chamber and the onion bulbs rested on this ring (see Appendix, Fig. A4). The vibration of the shaker pin was measured prior to the tests and no RF was found above 200 Hz. The vibration was visually inspected in the proprietary software (PSV software© v8. Polytec Ltd., UK) at lowest RF with help of profile lines. Each onion was also weighed. The SS1 bulbs were measured in a hexagonal pattern near the equator while lying on their side with 18 measurement points (6 on the inside and 12 on the outside). Two straight profile lines were inspected at RF, one near the neck and one nearer the base of the bulb (Fig. 1).

On the last sampling day of the storage experiment with 36 inoculated Elk bulbs, a ring was defined around the neck of the onions consisting of 42 points, so that 2 different hexagonal profile lines could be analysed: one closer to the neck and one slightly further away (Fig. 2). The data representing the profile lines around the neck were saved. Recorded signals were smoothed (Savitzky–Golay), normalised, averaged (over all data points), and peaks detected to identify RFs in the fast-Fourier-transform (FFT) of the initial signal (Matlab©, The Mathworks, MA, USA). The individual signals were very similar to the averaged signal (see Appendix 1, Figs. A2 and A3). Then the dynamic stiffness coefficient was calculated presuming that each onion bulb is near enough spherical according to the formula (Cooke, 1972):

$$S = f^2\, m^{2\,(-3)}$$

where S is stiffness, f the RF and m equals mass.

2.2.4. Single-point laser Doppler vibrometry

Experiments to evaluate different ways of data-processing on the signals collected by means of LDV were carried out. A portable single-point LDV device was used to measure sample onion bulbs (PDV 100, Polytec Ltd., UK. See Appendix 1, Fig. A4) and all samples were weighed. To measure LDV values, the cultivars Setton, Arthur, Centro bulbs were excited with a swept sine 200 to 2000 Hz on a shaker and five sensor measurements taken at one spot near the bulb neck, then data were processed as above. However, the data from Romy bulbs were analysed three different ways, i.e. by means of a) visual interpretation with the LDV software, b) by automatically performing calculations (Appendix 2) with the five measurements (Landahl, 2007) or c) by automatically analysing each signal individually with the mass spectrometer analysis package of Matlab. The processing procedure is described in Section 3. Damping was estimated by half-power bandwidth of the RF peak as commonly used in physical testing. In onion bulbs it was expected that in the majority of samples, the damping would be less in firmer bulbs. Therefore, the ratio between stiffness and damping was calculated to enhance the separation of differently treated onion groups (Landahl & Terry, 2020).

During field trials (cultivars Jagro, Forum, Solution) and packhouse visits (cultivars HAISH, Kamel, F, G), a miniature impulse hammer (086E80, PCB Piezotronics Inc., NY, USA) was introduced in order to excite vibration. The hammer impulse was capable of exciting RFs over a broad frequency range. The signal settings were, sampling frequency = 48 kHz, sample

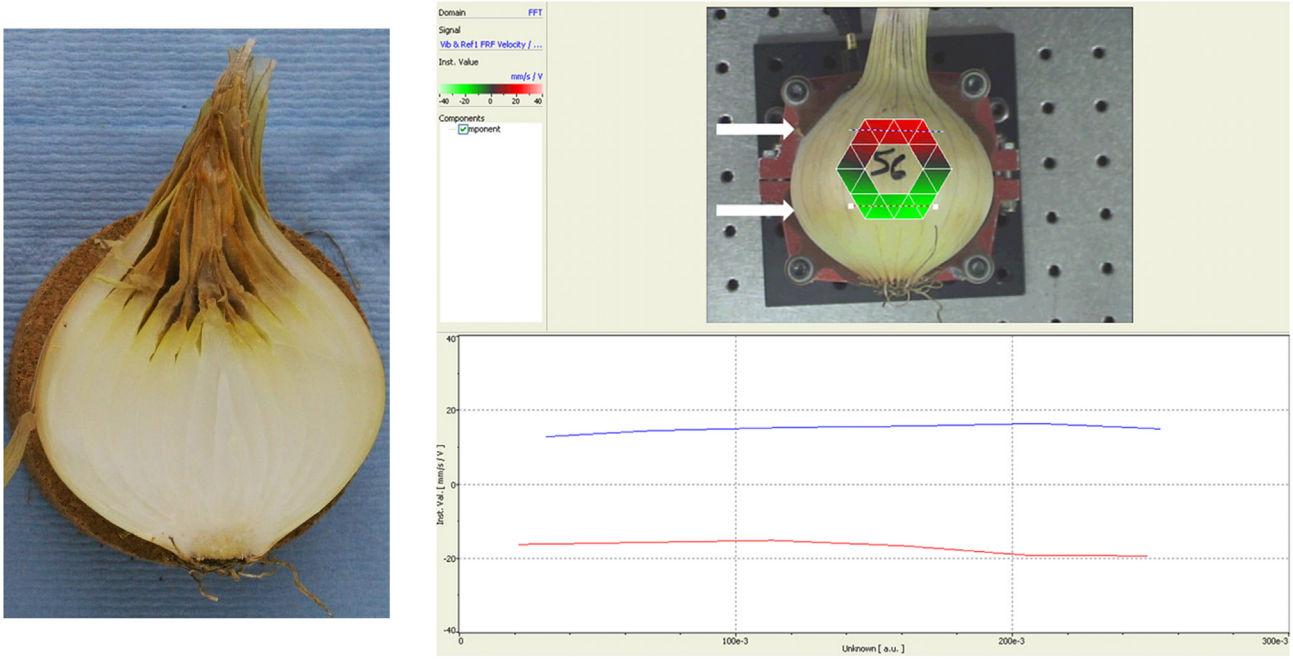


Fig. 1 – Sample 56 of SS1, which showed severity 3 neck rot (left). Snap shot of the proprietary software in analysis mode (right). On top a photograph of the analysed sample with the measurement grid overlaid (18 readings). The two dotted lines (arrows) through the grid in the top photo indicate the positions of the profile lines depicted in the bottom diagram.

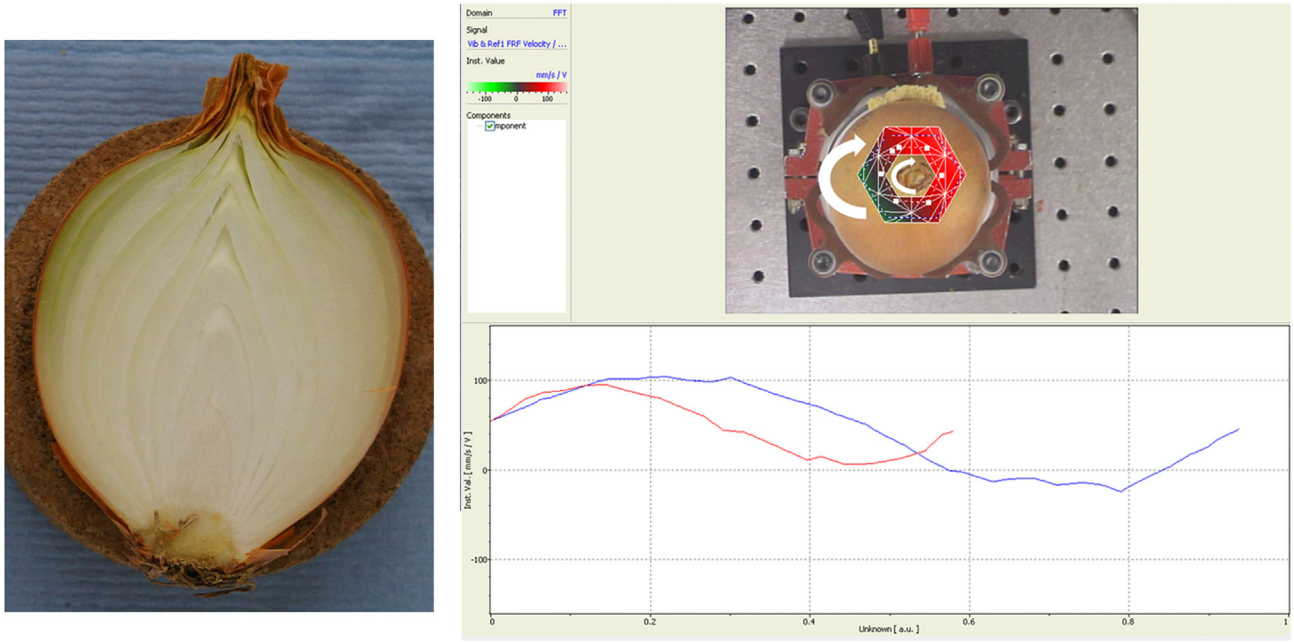


Fig. 2 – Sample 4 of Elk, which was inoculated with *Botrytis allii*, but shows no sign of infection after 3.5 months storage at 4 °C (left). Snap shot of the proprietary software in analysis mode (right). On top a photograph of the analysed sample with the measurement grid overlaid (42 readings). The two hexagonal dotted lines (arrows) through the grid in the top photo indicate the positions of the profile lines depicted in the bottom diagram.

length 2048 data points (cultivar Solution: 4096), sampling duration 42.7 ms (Solution: 85.3 ms), bandpass from 200 to 2,000 Hz (Solution: 10-3,000 Hz) and three impacts (Solution: three times three). The threshold value for predicting, if the bulb had rot, was calculated with stiffness divided by estimated damping value (half-peak bandwidth). For the three packhouse trials, measurements were carried out 3-times by means of single-point LDV with one impact each at neck, equator and base (HAISH three impacts each at neck or base).

2.2.5. *Statistics*

All statistical analysis including analysis of variance (ANOVA) was performed with Genstat (v. 15, VSN International Ltd., UK). Classification was performed on observed defects, then a threshold of the non-destructive data was determined by choosing the upper quartile point of observed rotten onions as cut-off value. Then the bulb's predicted classification was performed according to the threshold value, and the predicted values were compared to those observed. Clearly, because of the chosen cut-off value, a quarter of rotten onions would remain in the predicted sound lot of onions, but crucially, depending on the performance of LDV data-processing chosen, the ratio of sound to rotten onion bulbs correctly sorted would differ.

3. Results

Initially sampling was performed from onion batches with high disease incidence or which were inoculated with *B. allii*. This was done to develop a method to detect neck rot by LDV showing typical signals for sound and defective onion bulbs. In addition, batches of onions with multiple defects were analysed to explore if defects other than neck rot could be detected and segregated from each other and from sound bulbs. Subsequently, field trials were conducted with the intention of producing onion batches with high incidence of neck rot to test the efficacy of LDV to detect infected bulbs even with low severity. Lastly, the LDV set-up was taken into three commercial packhouses at the quality control station.

3.1. *Demonstrating scanning LDV profile of defective onion bulbs*

The stiffness of 27 successfully inoculated SS1 onions (Table 1) measured by means of scanning LDV or compression test showed no significant difference versus sound bulbs (Table 2). The profile lines for sound and diseased onions were unexpectedly flat (Fig. 1). In contrast to the assumption that the RF is a characteristic value of the whole object, where the disturbance in structure caused by fungal decay should lead to a noisy signal.

In the examination of profile lines around the neck of an infected bulb a disturbance was visible as an irregular vibration (Fig. 3) in contrast to the profile of a sound bulb, which showed smooth waves (Fig. 2).

3.2. *Comparison of defect detection by force deformation versus scanning LDV*

In total, 134 cultivar Arthur onions were taken from the grading line and measured by means of scanning LDV (Table 1). The majority of these were from the reject pile (n = 104), but uncut. After measuring non-destructively, the onions were cut and

Table 1 – Overview of descriptors for onion bulbs measured by means of LDV in the experiments.

Section in text	Demonstrating scanning LDV profile of defective onion bulbs		Comp. of defect detection by force deform. vs. scan. LDV	Classification of onions at pack house to test single-point LDV on onion batches with low defect incidence			
Cultivar	SS1	Elk	Arthur	HAISH	Kamel (red)	Anonym. "F"	Anonym. "G"
Number of bulbs	62	36	134	100	95	100	99
Size				60/80	60/75	80/90	80/90
Store temperature	20 °C	4 °C					
Store duration	1 month	3.5 months					
Treatment	Inoculated, laboratory	Inoculated, laboratory	Packhouse rejected and sound	Packhouse rejected and sound	Packhouse rejected and sound	Packhouse rejected and sound	Packhouse rejected and sound
Defect reported	27 rot	2 rot	104 rejected	1 rot, 24 bruise	4 rot, 2 maybe	3 rot	2 rot, 4 bruise
Section in text	**Classification of multiple cultivars of infected onions by means of single-point LDV with batches of high neck rot incidence to establish threshold values**						
Cultivar	Centro	Arthur	Setton	Romy	Forum	Jagro	Solution
Number of bulbs	246	249	254	353	278	251	390
Size				70/90			
Store temperature	3 °C	3 °C	3 °C		15 °C	15 °C	15 °C
Store duration	5 months	5 months	5 months		11 weeks	10 weeks	9 weeks
Treatment	Inoculated, laboratory	Inoculated, laboratory	Inoculated, laboratory	Packhouse rejected and sound	Field trial, grown from susceptible sets	Field trial, grown from susceptible sets	Field trial, grown from infected seed
Defect reported	87 rot	109 rot	62 rot	26 rot	122 rot	74 rot	224 rot

"SS1" is a super sweet variety with low pungency.
"Size" is reported by the suppliers as a minimum and maximum of millimetres. This relates to having the onions sorted on a sieve style grading machine.

Table 2 – Characteristic average values of sound and diseased SS1 onions (load at 3 mm [N], mass [g], RF [Hz], stiffness [10^6 Hz^2 $g^{2/3}$]). The least significant difference is shown to the right (l.s.d.).

SS1	Day 0	After 4 weeks		
		No disease	Diseased	l.s.d.
Load @ 3 mm		98.9	97.1	9.83
Mass	188	168	175	20.9
RF	529	586	558	99.2
Stiffness	10.3	11.3	10.9	3.72

these characteristics were found: 59 good, 30 sprouting, 15 double-hearted, 14 watery and 10 rotten. Some onion bulbs had more than one defect, but watery > rotten > sprouted were regarded before double hearted (six samples were omitted). The observed rots appeared to be of bacterial origin. The stiffness assessed destructively (by slope of the force-deformation curve before break) was significantly lower in rotten onions, than the rest and lower in watery onions than in sprouted bulbs (Fig. 4). On the other hand, the stiffness assessed non-destructively by scanning LDV was significantly lower in watery and rotten onions, than in the rest (Fig. 4).

The shaker used to initiate vibration of the onions was identified to have a time lag in the reference measurement and the set-up with an amplifier was deemed to add to the problem. While this did not result in a problem with calculating RF, it made the recording of the full-length reference and LDV signals more challenging. It was decided to excite samples with a miniature instrumented impulse hammer fitted with an accelerometer in packhouse trials, in order to trigger the recording of both reference and LDV signals promptly.

3.3. *Classification of multiple cultivars of infected onions by means of single-point LDV with batches of high neck rot incidence to establish threshold values*

For bulbs of cultivars Setton, Centro and Arthur, which were inoculated with different *B. alii* strains and which showed high disease incidence (Table 1), it was possible using LDV to separate sound bulbs from bulbs with about 10% rot (severity 2) after calculating the stiffness value (Fig. 5).

Visual inspection after non-destructive measurement and cutting showed a disease incidence of 7.9% of the Romy onions. After performing this trial, it was found that the best performing data-processing technique was option 'c' in Section 2.2.4. Data processing was optimised as follows: the signals were automatically loaded into the software's mass spectrometry toolbox, then down-sampled to remove noise (spikes) from the FFT spectrum (see Appendix 1, Fig. A5). After that a baseline regression was performed in order to obtain an even base for the peaks in the signal (see Appendix 1, Fig. A6). Then the whole spectrum was smoothed to make peak detection easier (see Appendix 1, Figs. A7 and A8). Lastly a minimum was chosen for a peak at lower frequency than the maximum peak, in order to exclude noise from sub-optimal excitations. Peaks of lower frequency than the maximum peak at least a third of its height were saved (Landahl, 2007). This data processing procedure allowed for the analysis of

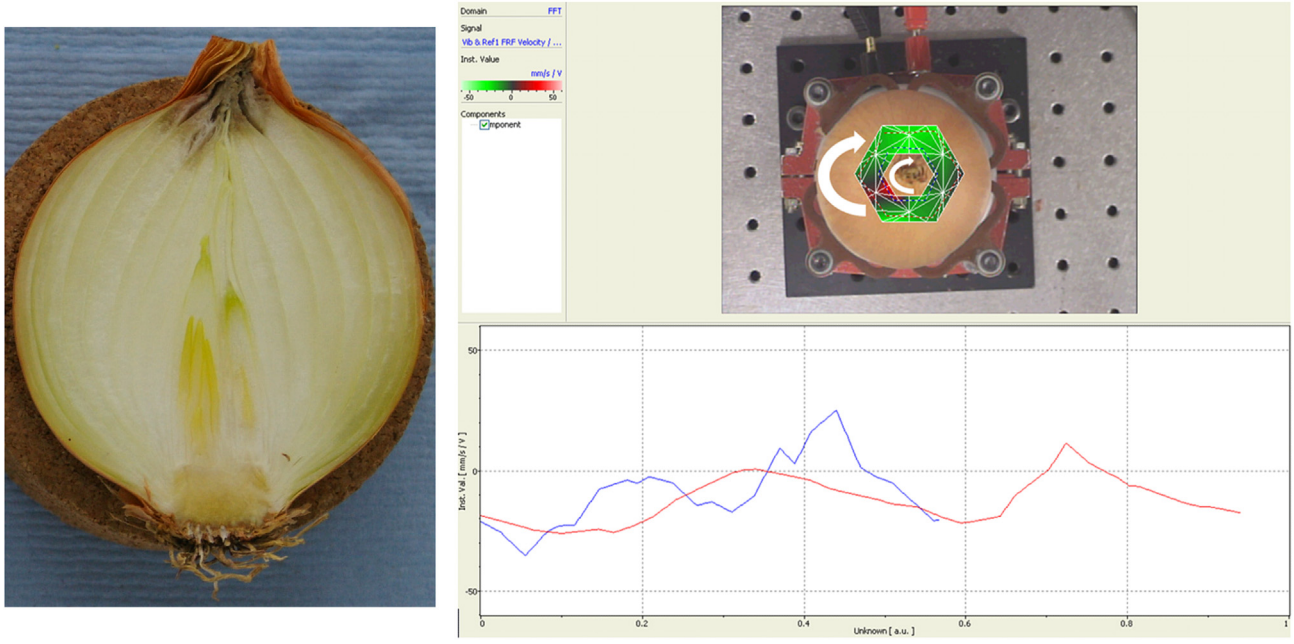


Fig. 3 – Sample 5 of Elk, which was inoculated with *Botrytis allii*, with severity 1 neck rot symptoms after 3.5 months storage at 4 °C (left). Snap shot of the proprietary software in analysis mode (right). On top a photograph of the analysed sample with the measurement grid overlaid (42 readings). The two hexagonal dotted lines (arrows) through the grid in the top photo indicate the positions of the profile lines depicted in the bottom diagram.

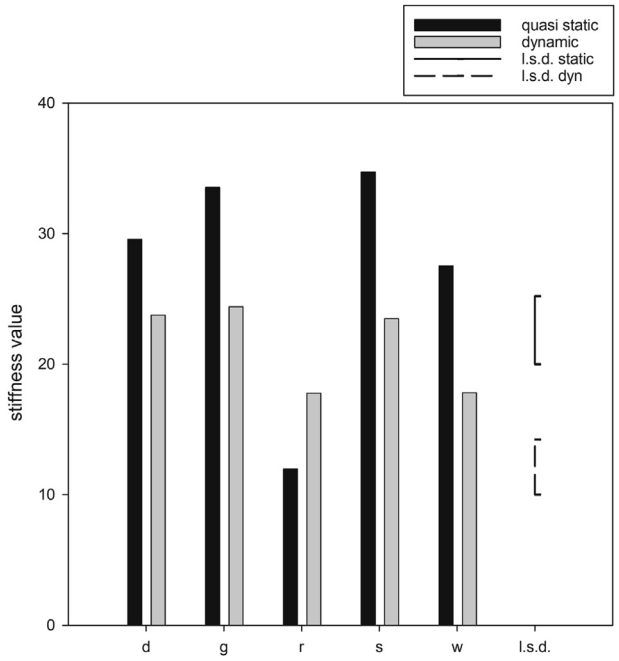


Fig. 4 – ANOVAs of stiffness measured quasi-static [N mm^{-1}] and dynamic [10^6 Hz^2 g$^{2\ (-3)}$] on graded Arthur onions. Bars indicate the average values. Error bars indicate the 5% least significant difference (l.s.d.). d = double hearted, g = good, r = severely rotten, s = sprouting and w = watery outer scale/mildly rotten.

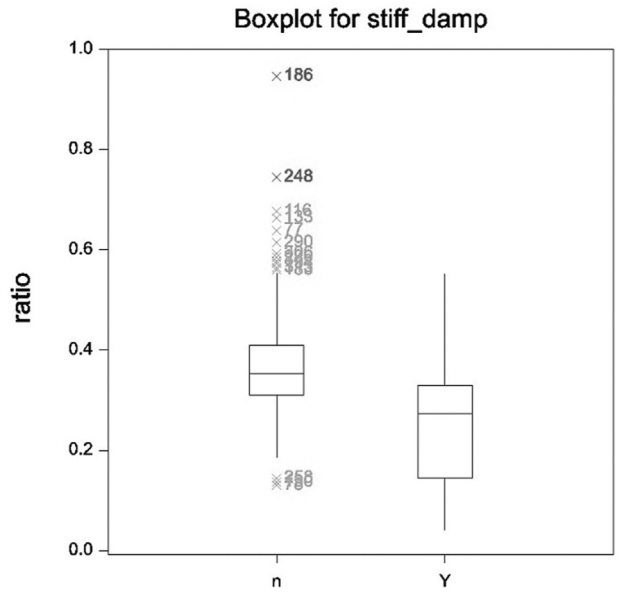


Fig. 6 – Boxplots of stiffness/damping ratio [10^6 Hz^2 g$^{2\ (-3)}$] vs. diseased (Y) or not diseased (n) of Romy onions. Boxes indicate the upper and lower quartile around the mean and the line in the box indicates the median. Bars stretching from the boxes indicate the minimum and maximum value. Outliers are indicated with × and number.

peaks, which describe a mode shape of lower complexity (e. g. simple oblate prolate vibration). These have been found to correspond with fruit quality parameters in the past (Huarng et al., 1993).

Using the lower quartile point of the non-diseased bulbs as the threshold, the sorted lot would only have had 3.2% infected bulbs (Fig. 6), while keeping two thirds of the sound onions, which otherwise would have gone to waste. The threshold can be chosen to optimise for less false positives or false negatives according to the grading needed.

Simple classification with stiffness per damping ratio of the field trial data yielded these numbers: Forum onions from sets would have had 109 of 156 sound onions identified correctly and 103 of 122 rotten onions removed. The cultivar Solution group could have had 115 of 166 sound onions detected correctly and 189 of 224 rotten onions removed. The cultivar Jagro lot would have had 129 of 177 sound onions recognised and 68 of 74 rotten onions removed, therefore had this batch been graded in this way only 4.4% rotten bulbs would have remained compared to 29.5% before sorting. It should be noted that the initial percentage of diseased onions would be unrealistically high for commercial lots. As

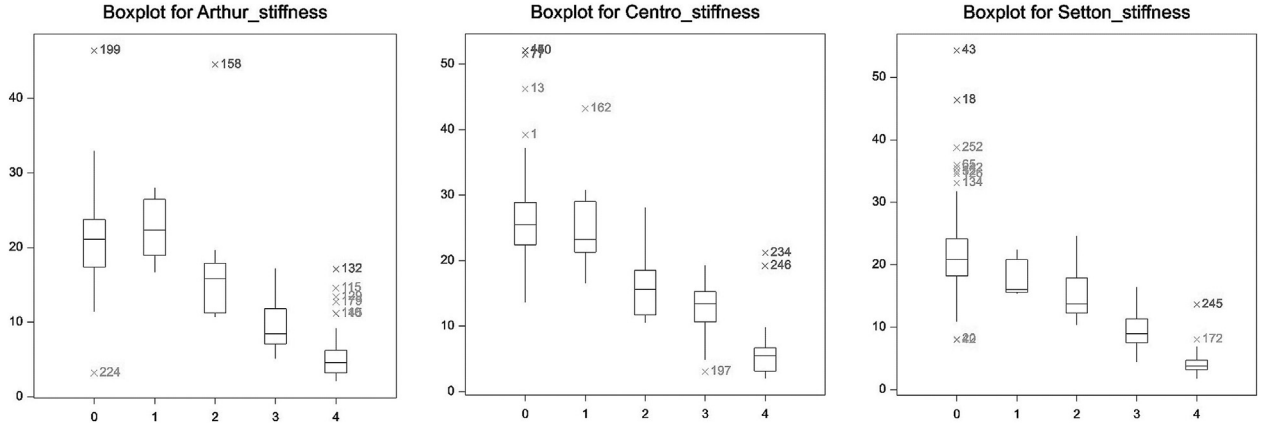


Fig. 5 – Boxplots of stiffness [10^6 Hz^2 g$^{2\ (-3)}$] vs. disease severity of neck rot inoculated Arthur, Centro, and Setton bulbs after 5 months storage. Boxes indicate the upper and lower quartile around the mean and the line in the box indicates the median. Bars stretching from the boxes indicate the minimum and maximum value. Outliers are indicated with × and number. Severities (see Appendix 1, Fig. A1): 1 up to 5%, 2 up to 10%, 3 up to 25%, 4 above 25%.

explained above, a high infection rate was intended in the field trials in order to analyse the possibility to classify disease severity. It was shown that LDV was capable of separating sound and 5%-rotten onions (Fig. 7). These results emphasise the capability of the LDV technique to accurately detect even bulbs with low disease severity. Certainly the operator would be able to choose a suitable threshold value, which would benefit from a data base of previously collected data from different onion cultivars and origins to calibrate an automated grading machine.

3.4. *Classification of onions at a pack house to test single-point LDV on onion batches with low defect incidence*

Onions measured at packhouse quality control centres using LDV were separated into sound and defective groups, despite only a small incidence of defective bulbs being present in a lot (Table 1). It was not necessary to merge the different values collected from one bulb (e.g. average); the results were significantly different between diseased and not diseased bulbs (F-probability) using values of individual impacts (Appendix 1, Table A1). It was found, that equator and neck signals are most useful to detect neck rot and bacterial rot (Table A1). The RF best separated onion bulbs with rot, which would mean it is not necessary to weigh the bulbs and calculate the stiffness value (Table A1). That said, a high percentage of sound onions would be graded out with a simple thresholding approach as can be seen in Fig. 8. Therefore, establishing a database (calibration) for system learning is necessary for implementation in a grading line.

4. Discussion

LDV is a non-invasive technique, which was shown to be capable of providing a rapid means of detecting internal rots in onions. Sprouting and double hearted bulbs could not be differentiated from sound onions. Detecting internal (invisible) disease at the sorting line provides a real potential of increasing grading reliability and allows growers to decrease waste.

4.1. *Demonstrating scanning LDV profile of defective onion bulbs*

The analysis of spatial bulb vibration collected by means of the scanning LDV made clear that measurements need to be taken near the neck if *B. allii* infection is to be detected. The importance of positioning a sample towards a sensor head has been discussed for visible and near infrared spectroscopy measurements when attempting to identify internal rots in onions (Kuroki et al., 2017), where it was found that spectral features differed depending on test location. In our study, excitation position was shown to be less critical than positioning of the laser beam for measurement. Data processing needs to be developed to filter out noisy signals, in order to gain repeatable results so that bulb quality can be interpreted.

4.2. *Comparison of defect detection by force deformation versus scanning LDV*

In this experiment it was found to be more useful to visually inspect the defect or disease by cutting the bulbs and record these data as reference. In this trial it was shown, that a high percentage of good onions are graded out on the commercial grading line using current methods. The non-destructive technique was capable of separating onions even with low severity bacterial rot. This indicates potential of increasing the efficacy of grading and could allow growers to decrease waste by sorting out mildly defected onions before the defect becomes more severe.

4.2.1. *Classification of multiple cultivars of infected onions by means of single-point LDV with batches of high neck rot incidence to establish threshold values*

In delivered batches, it was possible to separate sound bulbs from bulbs with only 10% defective cut surface area. After

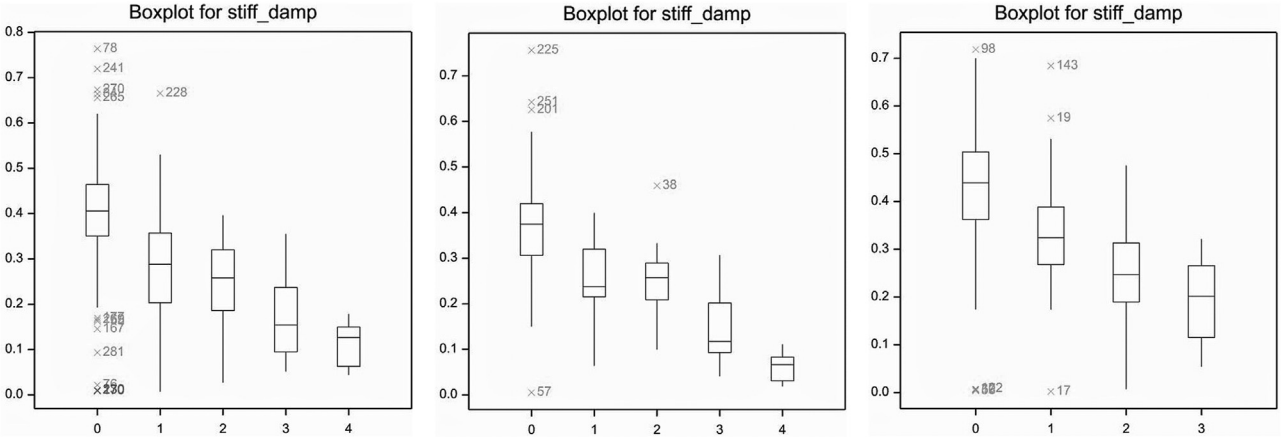


Fig. 7 – Boxplots of stiffness/damping ratio [10^6 Hz^2 $g^{2\,(-3)}$] vs. disease severity of cultivars Forum (left), Jagro (middle) and Solution (right) onion bulbs after 9–11 weeks storage. Boxes indicate the upper and lower quartile around the mean and the line in the box indicates the median. Bars stretching from the boxes indicate the minimum and maximum value. Outliers are indicated with × and number. Severities (see Appendix 1, Fig. A1): 1 up to 5%, 2 up to 10%, 3 up to 25%, 4 above 25%.

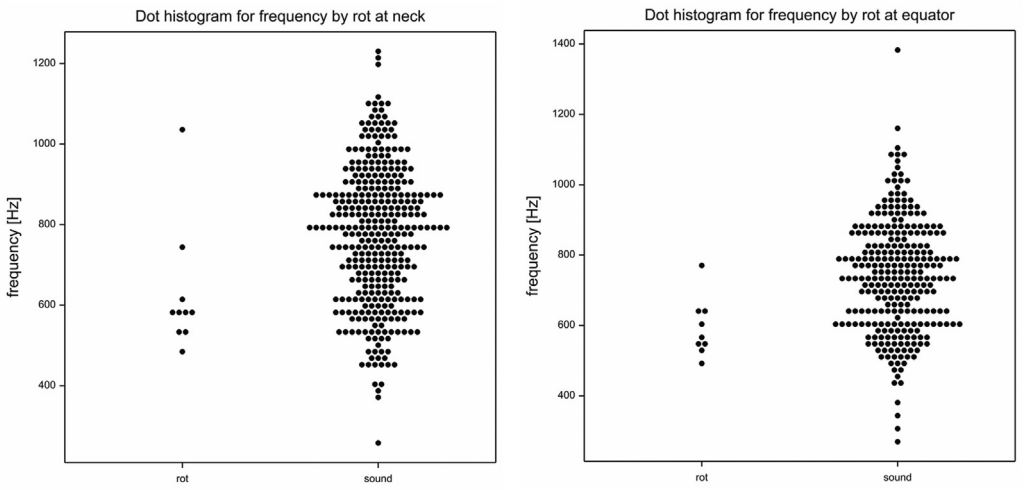


Fig. 8 – Dot histograms of onion bulb frequencies with and without rot measured by means of LDV. Left: Excitation was applied near the neck on HAISH, Kamel, F and G bulbs (HAISH: average of three impacts. Rest: one impact). Right: One excitation was applied on the equator of Kamel, F and G bulbs.

storage, onions that were grown in controlled field trials showed that LDV was capable of separating sound and rotten onions with only 5% defective area. The classification was performed on stiffness divided by estimated damping values. The signal only needed to be minimally processed due to the development of an optimised impact methodology using an instrumented hammer. This approach worked very well in the bench-top set-up used in the laboratory and in the packhouse testing. LDV is closely related to the acoustic impulse response technique, which has been examined for the use on fruit and vegetables to non-destructively determine ripeness or storage defects (Karthickumar et al., 2018; Landahl & Terry, 2020). However, the authors believe LDV to be a superior sensor compared to a system that relies on sound (microphone) in a noisy packhouse, or an accelerometer which has to be in contact to the sample.

4.2.2. *Classification of onions at a pack house to test single-point LDV on onion batches with low defect incidence*

The quality control station visits revealed, that RF on its own showed significant differences between size-graded sound and defect onion bulbs, so that it would not be necessary to weigh bulbs in order to calculate the stiffness value. For grading LDV would compete with sophisticated imaging techniques with speeds and affordability approved by the industry.

Packhouse trials confirmed that signals collected after impacting the neck or equator are most useful to detect neck rot and bacterial rot, respectively. The methodology evolved from scanning LDV to evaluate the vibration over a whole bulb to a single-point LDV (quicker and less expensive). Signal processing has been shown to lead to different results for different types of batches and cultivars. The vibration analysis lends itself to further exploration of the best marker value, which describes internal defects in onions as the technique becomes more widespread in agricultural analyses (Gonzalez et al., 2020). Furthermore, if LDV becomes more accepted, the need for comparison with destructive methods, could be replaced by increased confidence in collected data sets.

In a typical packing line, an industrially customised single-point LDV would be most desirable, since it can be made as simple and rugged as possible and might be produced cheaper than standard LDV models. In addition, it would be desirable to avoid an excitation that requires positioning of the bulb in a certain way However, the reference values available from the modal analysis hammer could give valuable specifications on impact duration and force required for a successful vibration measurement to be recorded. At the packhouse a suggestion was made that this technique would be suitable for high value produce. In the case of onion it could potentially be implemented for bulbs sold in nets of three, since they are singulated before netting.

5. Conclusion

It was shown that defect incidence and different severities of disease can be predicted with RF using an optimised desktop LDV set-up. It would be necessary to build a calibration database of values for different onion cultivars and origins to implement LDV in a commercial sorting line. The non-invasive LDV technique is a prototype to measure internal defects, which can be a useful decision tool in onion grading, and for other commodities where internal defect detection is required.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work formed part of a Hortlink Defra feasibility study (HL1103) and the larger Technology Strategy Board project (TSB100892, TP320-257) financially supported by the UK Government (Department for Environment, Food and Rural Affairs) and industrial partners (Allium & Brassica Centre, G's Fresh, Moulton Bulb Co. Ltd., Polytec UK Ltd., Rustler, S.E.P., Stourgarden).

Appendix 1



Fig. A1 – Neck rot severities in onions: 1 up to 5%, 2 up to 10%, 3 up to 25%, 4 above 25%.

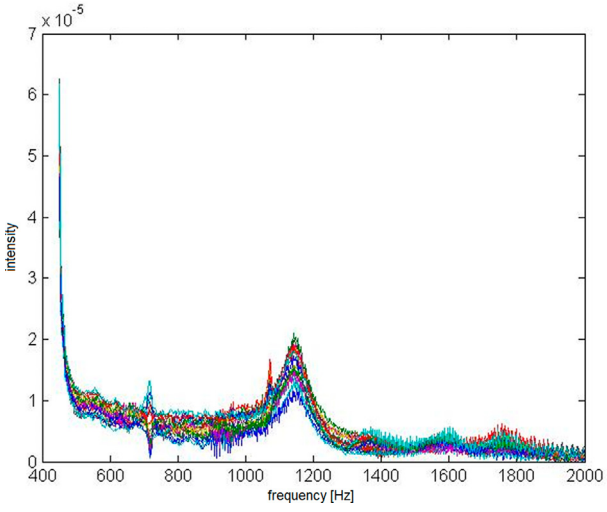


Fig. A2 – Vibration spectra collected by means of scanning LDV in a ring pattern on onion bulb.

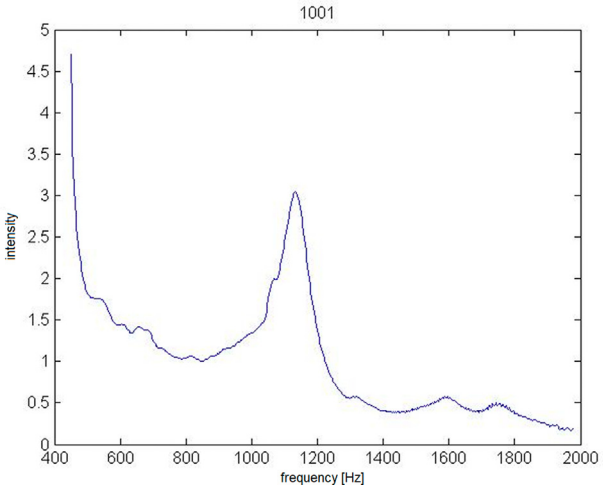


Fig. A3 – Average of vibration spectra collected by means of scanning LDV in a ring pattern on onion bulb, compare Fig. A2.

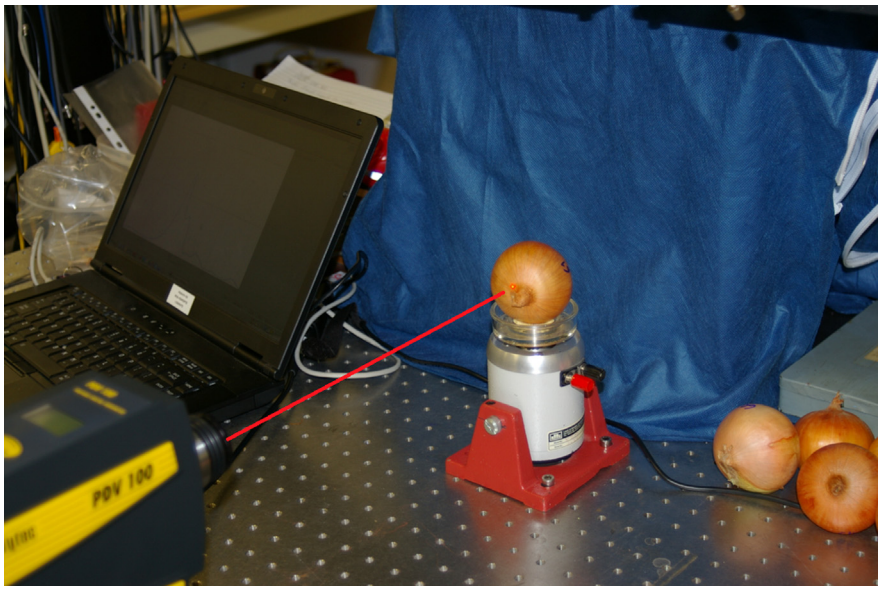


Fig. A4 – Set-up of single point LDV measuring onion vibration excited by shaker.

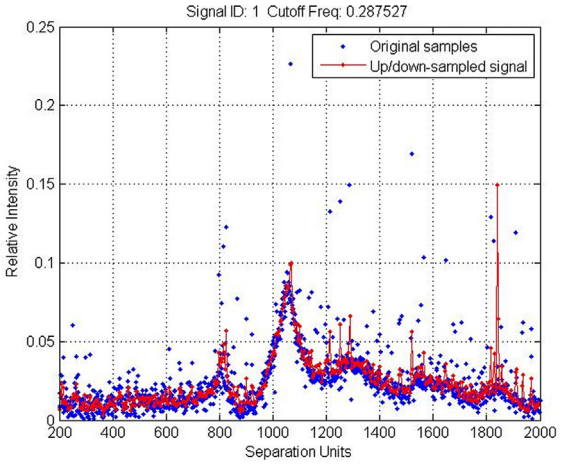


Fig. A5 – A noisy signal from a RF measurement of an onion. Representation of down-sampling the data.

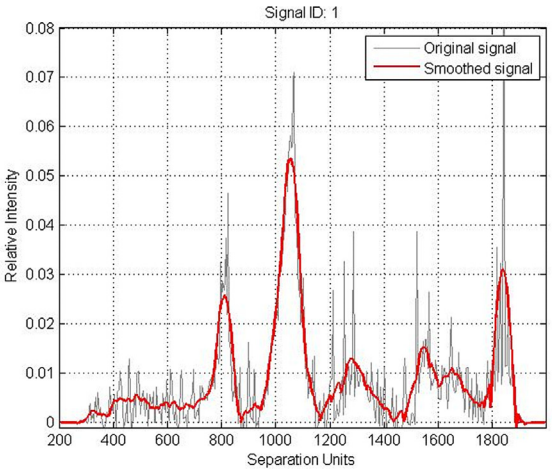


Fig. A7 – Representation of smoothing the data from Fig. A6.

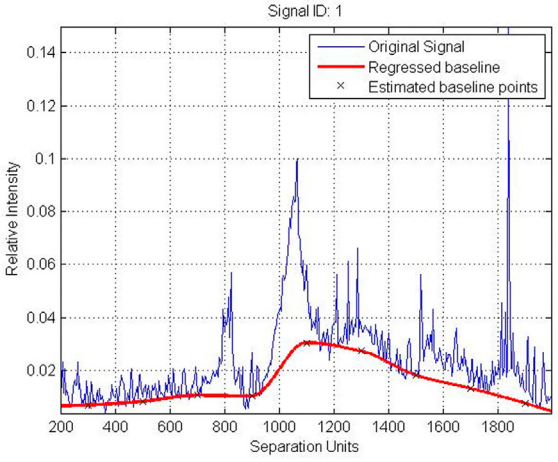


Fig. A6 – Representation of baseline correction of the data from Fig. A5.

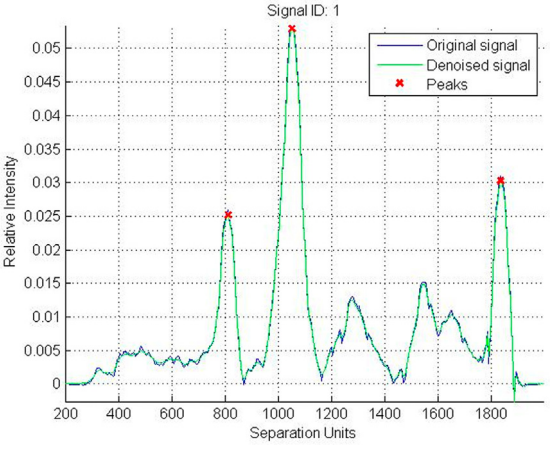


Fig. A8 – Representation of peak detection in the data from Fig. A7.

Table A1 – Statistical results of ANOVA between two groups (no defect and defect including maybe defect). The "statistics with values from 3 impacts" indicate F-probability with only factor defect. The "statistics with individual values per impact" show F-probability for each impact position × defect.

Impact location	HAISH	=	Kamel	F bulbs	G bulbs
	Neck	Base	Neck, equator, base	Neck, equator, base	Neck, equator, base
F-test defect vs. sound					
Mass	0.891	=	0.518	0.937	0.803
Statistics with values from 3 impacts					
Frequency	0.015	0.081	0.016	0.073	0.073
Stiffness	0.029	0.105	0.020	0.179	0.232
Damping	0.662	0.937	0.138	0.763	0.013
Stiff/damp	0.082	0.132	0.005	0.154	0.072
Statistics with individual values per impact (same as above)					
Frequency neck			0.276	0.044	0.031
Frequency equator			0.016	0.043	0.042
Frequency base			0.258	0.658	0.454

Appendix 2

Matlab procedure to calculate RF and damping value from onions excited by means of shaker.

```
% calculation of point laser data
% on frequency spectrum
% frequencies are identified with Pal's algorithm
% diff does not work with smoothing (?)
% calculate bandwith of damping at 1/sqrt of first peak

%empty workspace
clear all
% freq: x-axis and frequency value of measurement (index)
points in power spectrum
time=200:1.25:2000;
% load file
z0=dlmread('C:\') ;
% determine number of rows to input in the loop -> tells us
% how many times the loop has to run
row=size(z0,1);
col=size(z0,2);
% prepare variable to collect results
comb=[];
peak=[];
% loop for processing measurements done on a fruit
for nr=1:row
    % (useful) signals
    z1 = z0(nr,2:col) ;
    % label
    lab1 = z0(nr,1) ;

    figure(1)
    clf
    plot(time,z1)
    % smoothing (must be done on columns)
    time=time' ;
    z1=z1' ;
    z11 = mssgolay(time,z1,'SPAN',100) ;
    time=time' ;
    z11=z11' ;
    % mean - normalizing (must be done on columns)
    %z11 = msnorm(time,z11,'Method','Mean');

    % high pass filter  "hpf"
    hpf = 50;
    for i = 1:length(z11), logit(i) = 1/(1+(1/(exp((i/2)-
hpf))));end;
    z111 = logit.* z11;
```

```
    % low pass filter "lpf" (hpf reverse)
    lpf = wrev(logit);
    z111 = lpf.* z111;
    figure(3)
    clf
    plot(time,z111)
    %function ix=peakseek(y)
        %ix will contain the indices into vector y of the
function peaks.
        %y(ix) will contain the actual function values of the
peaks.
        % made by Jancsok P 1999
        % find the local maxima of row vector
        ix = find(z111 > [+inf, z111(1:col-2)]  &  z111 >
[z111(2:col-1), +inf]) ;
        % peak indeces "pix" at least 40% of absolute maximum
peak of each vector
        pix = [] ;
        for i = 1:length(ix),
            if z111(ix(i)) > 0.4*max(z111),
                pix = [pix ix(i)] ;end
            if z111(ix(i)) == max(z111),
                maxind = ix(i) ;end
        end
        maxfreq = time(maxind)
        % prepare empty matrix for damping value of maximum
peak
        g = [];
        % damping as half power bandwith calculated of maximum
peak
        for s = maxind-99 : maxind
            if (z111(s-1) < (max(z111)/sqrt(2)) & z111(s) >=
(max(z111)/sqrt(2))),
                    g = [g s];end
        end
        % prepare empty matrix for damping value of maximum
peak
        h = [];
        for y = maxind+1 : maxind+100
            if (z111(y-1) > (max(z111)/sqrt(2)) & z111(y) <=
(max(z111)/sqrt(2))),
                    h = [h y];
            end
        end
        len=length(h);
        if length(g) > 0 & len > 0
            dampmax = time(h(len))-time(g(1))
        else dampmax = 0
        end
```

```
        % chosen peak: indeces "ind" at least 100 points into
vector. sort
        % of high pass filter: 100 * 1.25Hz = 125Hz, 125Hz +
200Hz = 325Hz
        % minimum
        ind = [];
        for r = 1:length(pix),
            if pix(r) > 100,
                ind = [ind pix(r)];end
        end
        peakdet = time(ind);
        % append zeros
        pad = zeros(1,5);
        ind = [ind pad];
        peakdet1 = [peakdet pad];
        % make sure every file is the same amount of points
long (necessary for Matlab)
        peakdet2 = peakdet1(1,1:5)
        % prepare empty matrix for damping value of chosen
peak
        g = [];
        % damping as half power bandwith calculated of chosen
peak
        for s = ind(2)-99 : ind(2)
            if ind(2) == 0,
                g =[];
            elseif (z111(s-1) < (z111(ind(2))/sqrt(2)) &
z111(s) >= (z111(ind(2))/sqrt(2))),
                    g = [g s];
            end
        end

        h = [];
        for y = ind(2)+1 : ind(2)+100
            if ind(2) == 0,
                h =[];
            elseif (z111(y-1) > (z111(ind(2))/sqrt(2)) &
z111(y) <= (z111(ind(2))/sqrt(2))),
                    h = [h y];end
        end
        len=length(h);
        if length(g) > 0 & len > 0
            damp = time(h(len))-time(g(1))
        else damp = 0
        end
        comb = [comb
            lab1 maxfreq dampmax peakdet2 damp] ;
end
% saving
eval('save results.asc comb -ASCII') ;
```

REFERENCES

Cooke, J. R. (1972). An interpretation of the resonant behaviour of intact fruits and vegetables. *Transactions of the ASAE*, 15, 1075–1080. https://doi.org/10.13031/2013.38074

Gonzalez, M., Budelli, E., Perez, N., & Lema, P. (2020). Acoustic techniques to detect eye formation during ripening of Emmental-type cheese. *Innovative Food Science & Emerging Technologies*, 59, 102270. https://doi.org/10.1016/j.ifset.2019.102270

Huarng, L., Chen, P., & Upadhyaya, S. (1993). Determination of acoustic vibration modes in apples. *Transactions of the ASAE*, 36(5), 1423–1429. https://doi.org/10.13031/2013.28481

Kamal, T., Chen, S., Khan, I. A., Nawab, K., Zhang, T., Song, Y., Wang, S., Nadeem, M., Riaz, M., Khan, M. A. U., Zhu, B.-W., & Tan, M. (2019). Potential uses of LF-NMR and MRI in the study of water dynamics and quality measurement of fruits and vegetables. *Journal of Food Processing and Preservation*, 43, Article e14202. https://ifst.onlinelibrary.wiley.com/doi/10.1111/jfpp.14202.

Karthickumar, P., Sinija, V. R., Alagusundaram, K., & Yadav, B. K. (2018). Development of a sorting system for fruits and vegetables based on acoustic resonance technique. *Agricultural Mechanization in Asia, Africa and Latin America*, 49(1), 22–27.

Kim, D.-H., Lee, K.-H., Choi, C.-H., Choi, T.-H., & Kim, Y.-J. (2018). Development of real-time onion disease monitoring system using image acquisition. *Frontiers of Agricultural Science and Engineering*, 5(4), 469–474. https://doi.org/10.15302/J-FASE-2018213

Kim, W.-S., Lee, D.-H., & Kim, Y.-J. (2020). Machine vision-based automatic disease symptom detection of onion downy mildew. *Computers and Electronics in Agriculture*, 168, 105099. https://doi.org/10.1016/j.compag.2019.105099

Kuroki, S., Nishino, M., Nakano, S., Deguchi, Y., & Itoh, H. (2017). Positioning in spectral measurement dominates estimation performance of internal rot in onion bulbs. *Postharvest Biology and Technology*, 128, 18–23. https://doi.org/10.1016/j.postharvbio.2017.02.001

Landahl, S. (2007). Comprehensive evaluation of the acoustic impulse-response of apples as a measure of fruit quality [Doctoral dissertation]. In *Chapter 2, Dissertationes de agricultura*. K. U. Leuven nr. 743. ISBN: 978-90-8826-021-6 https://limo.libis.be/primo-explore/fulldisplay?docid=LIRIAS1714466&context=L&vid=KULeuven&search_scope=ALL_CONTENT&tab=all_content_tab&lang=en_US.

Landahl, S., & Terry, L. A. (2020). Non-destructive discrimination of avocado fruit ripeness using Laser Doppler vibrometry. *Biosystems Engineering*, 194, 251–260. https://doi.org/10.1016/j.biosystemseng.2020.04.001

Mosqueda, M. R. P., Tollner, E. W., Boyhan, G. E., & McGlendon, R. W. (2010). Predicting the economics of X-ray inspection technology in sweet onion packinghouses using simulation modelling. *Biosystems Engineering*, 105, 139–147. https://doi.org/10.1016/j.biosystemseng.2009.10.004

Nishino, M., Kuroki, S., Deguchi, Y., Nakano, S., & Itoh, H. (2019). Dual-beam spectral measurement improves accuracy of non-destructive identification of internal rot in onion bulbs. *Postharvest Biology and Technology*, 156, 110935. https://doi.org/10.1016/j.postharvbio.2019.110935

Wang, W., & Li, C. (2015). A multimodal machine vision system for quality inspection of onions. *Journal of Food Engineering*, 166, 291–301. https://doi.org/10.1016/j.jfoodeng.2015.06.027



https://dspace.org/

Detection of internal defects in onion bulbs by means of single-point and scanning laser Doppler vibrometry

Landahl, Sandra; Terry, Leon A.

2022-08-05
Elsevier
https://doi.org/10.1016/j.biosystemseng.2022.07.004
Landahl S, Terry LA. (2022) Detection of internal defects in onion bulbs by means of single-point and scanning laser Doppler vibrometry. Biosystems Engineering, Volume 221, September 2022, pp. 258-273

Downloaded from a DSpace repository. https://dspace.org/