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Piezoelectric transducers for real-time evaluation of fruit firmness. Part II: Statistical and sorting analysis

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ABSTRACT

This paper presents a statistical method for the calibration of an acoustic technique for the real-time evaluation of fruit firmness. The technique uses an experimental setup based on two standard piezoelectric transducers and exploits two novel stiffness indexes developed in the first part of this paper. Extensive experimental measurements show good correlation ($r = 0.930$, $R^2 = 0.865$) between the proposed non-destructive test and the traditional destructive Magness-Taylor test. An evaluation of the statistical significance (*t*-test) of the obtained regression model parameters has been performed and validates the method. The presented sorting analysis complements the physical detection techniques presented in the first part of the paper, allowing to classify individual kiwifruits with high accuracy and high prediction rate (~90%). The technology is suitable for industrial real-time and in-line applications aiming to improve warehouse stock management and market stock uniformity.

1. Introduction

In the field of postharvest evaluation of agricultural products the development of non-destructive techniques replacing intrusive sensors allows to perform repeated ripeness measurements on fruit stocks, therefore enabling sorting analyses on individual fruit basis and improving the overall quality of market products. The propagation methods proposed in the first part of this work [1] showed to be suitable for a non-destructive evaluation of kiwifruit firmness, which is notoriously well related to fruit ripeness [2–4]. A non-destructive technique for measuring kiwifruit firmness is very helpful in postharvest research, thus allowing repeated measurements on the same fruit during storage [5]. These techniques give tangible benefits by identifying the degrees of ripeness of postharvest products and enabling strategies which require more immediate and accurate decisions in logistic and warehouse context. The firmness of fruit at harvest time is extremely variable and uneven and, since ripe fruits produce an excess of ethylene which accelerates the ripening process of adjacent stocked fruits, if ripe fruits were not separated from firm fruits, the admissible storage time is reduced. Therefore, the ability of sorting agricultural products according to their firmness is of paramount importance in food market [6–12]. Indeed, modern quality criteria for agricultural products require a set of standard properties throughout the overall production, among which weight, size, sugar content and, as mentioned, ripeness [13,14]. Present state of the art references [6,7,9,10,15] report the importance of real-time sorting analysis to provide fast and low cost methods for classifying objects. In [6], a sorting machine capable to process fruit up to 7 fruits/s per lane with a two-grade sorting is developed, and successfully tested in a commercial packinghouse on kiwifruit. The study in [7] reports a commercial peaches sorting line for firmness based on fruit impact technique, which is capable to work at 8 fruit/s with good sorting repeatability by comparing real and predicted firm. In [9] various methods based on force response and sonic impulse are presented; furthermore, some examples of commercial testers capable of processing and sorting fruits at speeds up to 10 fruits/s are reported. In [10] software is developed to predict and sort fruit of different firmness with a non-destructive in-line impact device relying on an existing database. Other techniques, such as that presented in [15], rather than on mechanical parameters, are based on cross-combined optical and capacitive analysis and allow characterizing granular objects (cereal grains) with a throughput of 30 grains/s per channel. However, the speed of sorting, or rather the conveyor speed, could play an important role in the firmness prediction capability [16]. Paper [17] presents a sensor system based on piezoelectric devices and ultrasound techniques

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relying on the propagation characteristic of the item under test: our system exploits similar principles but operates at much lower frequencies.

This paper in depth investigates two indexes for firmness evaluation based on wave propagation models through fruits, namely the indexes S_3 and S_4 introduced in paper [1], whose main results are here highlighted: (i) the novel indexes based on sound propagation have shown small dependence on the contact position of the sensor on the fruit; (ii) the firmness determination is fast and compatible with the high throughput of industrial lines; (iii) the proposed indexes S_3 and S_4 demonstrated to be very sensitive to relative firmness variations during a storage time of 11 days, in a clear connection with the ripening process.

In the previous part of this work [1] we discussed how the non-destructive measurement analysis techniques have the significant advantage of allowing repeated measurements on single fruit samples and are therefore able to evaluate the effects of fruit ripening by monitoring the relative variations of the proposed stiffness indexes. In this second paper, we rather investigate the statistical correlation between the proposed propagation methods, which are based on a non-destructive test response, and the standard Magness-Taylor test, an intrusive test supposed to address the real firmness, but which also irremediably damages the fruit sample. In order to produce reliable analyses, an extensive set of measurements is performed on a statistically significant set of fruits. Furthermore, we will show how the results of the statistical analysis allow us to estimate the real firmness obtained with the Magness-Taylor test by using a predicted firmness value obtained with the non-destructive test. Hence, if the number of samples taken into account is sufficiently large to achieve a useful calibration, this prediction capability can be extended to all fruits of the same species [2]. The techniques are validated by means of a statistical inference analysis (*t*-test) that assigns the due confidence on the extracted regression parameters. Finally, a statistical sorting analysis that separates fruits into different ranges of firmness, as specified by the industry standard, is developed and demonstrates the capability of the above mentioned tests.

In Section 2 the statistical tools adopted are briefly recalled along with the experimental setup equipment. Moreover, a detailed description of both acoustic and intrusive methods follows. In Section 3 the statistical analysis technique is applied to experimental data and the results of the regression and correlation analysis are reported for each stiffness index. In Section 4 the sorting analysis is described and the results are illustrated for both the adopted indexes. Finally in Section 5 the conclusions are presented.

2. Materials and methods

This section describes in detail the experimental setup and first explains the non-destructive method derived from [1] and then the intrusive method [18,19] used for the evaluation of kiwifruit firmness. Though the stiffness indexes are those developed in [1], the non-destructive equipment and the proposed methodology for data analysis are valid for a wide range of acoustic techniques and electronic sensors. We will start this section with a brief review of the statistical methods adopted for the treatment of data [20–23].

2.1. Regression and inference analysis

The regression model used in this paper is the Ordinary Least Squares (OLS) model that allows studying the correlation between the non-destructive test and the intrusive test. The correlation coefficient *r* and the linear regression equation are defined according to Refs. [20,21].

The following notation is assumed. For a linear regression model of *n* fruit samples, given a data set $\{S,F\}$, the data $S = (S_1, S_2, \ldots, S_n)$ represents the results S_i of the non-destructive sensor while the data $F = (F_1, F_2, \ldots, F_n)$ represents the results F_i of the intrusive test. The linear regression equation is defined by $F_i{}' = bS_i + a$ where *b* is the angular coefficient, *a* is the intercept of the regression line, and $F' = (F_1{}', F_2{}', \ldots, F_n{}')$ represents the predicted values for the intrusive test for the *n* samples. The mean S_C of the *S* data (proposed method), the mean F_C of the *F* data (destructive method), the correlation coefficient *r* between the data *S* and *F*, and the determination coefficient R^2 are evaluated according to the formulae in references [20,21].

A value $R^2 \cong 1$ means that the regression line fits the data well, while $R^2 \cong 0$ indicates otherwise. If a small number of samples *n* is considered, an improved version, called adjusted determination coefficient $R^2{}_{\text{adj}}$, is calculated as well according to Eq. (1), as explained in [21]:

$$R^2_{\text{adj}} = R^2 - \frac{1 - R^2}{n - 2}. \tag{1}$$

As explained in [20], the confidence ranges (β_{lo}, β_{up}), $(\alpha_{lo}, \alpha_{up})$, and $(\gamma_{lo}, \gamma_{up})$, indicate the interval inside which the actual regression values β, α, and γ (respectively the actual slope, intercept and correlation coefficient) fall within a $100(1 - p)$ percent confidence, where *p* is the assigned confidence parameter. The ranges can be calculated from the available relatively small data set with the tabulated one-sided *t*-distribution $t_{p/2,\,n-2}$ with *p* confidence and $n - 2$ degrees of freedom [20].

The confidence interval (F'_{lo}, F'_{up}) of the regression equation is also calculated with the same method and is briefly recalled herein for this specific case:

$$F'_{lo} = F' - t_{p/2,n-2} \cdot s_{F'},\; F'_{up} = F' + t_{p/2,n-2} \cdot s_{F'}. \tag{2}$$

where $s_{F'}$ is the standard error of F' as defined in [20]. The confidence intervals are key indicators for an accurate sorting analysis as explained in the following sections.

In order to validate the regression model, we can perform an inference analysis with hypothesis test on *a*, *b* and *r*, by calculating their significance level with the Student's *t*-test [20]. The values t_b, t_a, and t_r will be used to indicate the Student's *t*-test evaluation results with a *p* probability respectively for *b*, *a* and *r*. The *p*-value of the Student's *t*-test indicates the critical significance level of acceptance of the null hypothesis. This test was used in order to validate whether the proposed regression models associated with our non-destructive technique can be reliably used instead of the destructive Magness-Taylor firmness test.

2.2. Plant materials

Fruit of kiwifruit vines (*Actinida deliciosa*) of different degrees of ripeness were harvested and transported to the laboratory facilities and immediately stored at a 4 °C.

2.3. Stiffness indexes based on propagation

The equipment for firmness evaluation is the same illustrated in the first part [1] and is here briefly summarized. The devices used are piezoelectric Q220-A4-303-YB bimorphs from Piezo Systems. A linear voltage amplifier EPA-104 from Piezo Systems and a DAQ board are used for actuation and sensing. During each measurement, single fruits are positioned between the two contact transducers, as shown in Fig. 1.

The setup consists of a mechanical apparatus bearing the kiwifruit on a soft-bed holder and clamping it between a piezoelectric sensor and a piezoelectric actuator. The distance Δl (m) between the piezoelectric devices is equal to the fruit diameter along the equator. A 250 μs sinusoidal pulse (positive-half) of 4.0 V