BIOSYSTEMS ENGINEERING 129 (2015) 288–297

Available online at www.sciencedirect.com

ScienceDirect

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

Research Paper

On-line firmness sensing of dates using a non-destructive impact testing device

Seyed Ahmad Mireei, Morteza Sadeghi*, Alireza Heidari, Abbas Hemmat

Department of Biosystems Engineering, College of Agriculture, Isfahan University of Technology, Isfahan 84156-83111, Iran

ARTICLE INFO

Article history:
Received 8 May 2014
Received in revised form
15 October 2014
Accepted 29 October 2014
Published online 21 November 2014

Keywords:
Conveyor
Load cell
Non-destructive test
Multiple regression
Partial least squares

Based upon a non-destructive falling impact test, a rapid on-line device was developed for assessing date fruits firmness. The device consisted of a conveyor unit used for carrying and throwing fruits onto a flat plate connected to a load cell and a data acquisition unit for acquiring the impact force time history. All the tests were carried out at three speeds (1, 1.5 and 2 m s^{-1}) of the conveyor belt. The firmness predictive models were initially developed using simple and multiple regressions with individual impact indices derived from the first half-wave. These indices were also computed for the first twenty positive half-waves of the impact signal and used for further regression analysis. Moreover, all data points of the first half-wave and the entire impact signal were used as independent variables in developing partial least squares regression models. Generally, a substantial increase in prediction power appeared when using the impact indices of the twenty positive half-waves (coefficient of determination in prediction (R_p^2) of 0.756 and standard deviation ratio (SDR) of 2.46) instead of the impact indices of the first half-wave ($R_p^2 = 0.527$, SDR = 1.74). Partial least squares models with the entire impact history led to slightly better results ($R_p^2 = 0.800$, SDR = 2.77) as compared to those developed from the first half-wave information ($R_p^2 = 0.776$, SDR = 2.61). The intermediate forward speed of 1.5 m s^{-1} indicated the best predictions in almost all different methods.

1. Introduction

Maturity grading of date palm fruits (*Pheonix dactylifera* L.) during harvesting and before delivery to the market is useful for decision-making on the harvesting schedule, thereby determining the optimal time for marketing and optimising storage management (Lien, Ay, & Ting, 2009; Schmilovitch et al., 1999). Like many climacteric fruits, firmness is one of the main factors in evaluating the maturity of date fruit as it can affect its future proper ripening (Mireei, Mohtasebi, & Sadeghi, 2014). Several traditional and standard methods, such as compression and penetration tests, have been introduced to reliably estimate the firmness of different fruits including the date fruit. Despite the accurate and reproducible results of these proposed methods, they all are destructive and time-consuming and therefore, cannot be implemented as on-line measuring techniques for fruit grading.

Several studies have addressed non-destructive and fast techniques for firmness prediction of various fruits and vegetables which some of them are commercially available including: optical-based methods which use near-infrared

* *Corresponding author*. Tel.: +98 (31)33913508; fax: +98 (31)33913471.
E-mail address: sadeghimor@cc.iut.ac.ir (M. Sadeghi).
http://dx.doi.org/10.1016/j.biosystemseng.2014.10.012

Nomenclature

adj. R_c^2	Adjusted coefficient of determination in calibration
ANN	Artificial neural network
C.V.	Coefficient of variation
Cal.	Calibration
D_c	Contact duration
df	Degree of freedom
F_p	Peak of impact force
HW	Half-wave
I_p	Peak impulse
LOOCV	Leave-one-out cross-validation
LVs	Latent variables
n	Number of samples
NIR	Near-infrared
NMR	Nuclear magnetic resonance
PLS	Partial least squares regression
R^2	Coefficient of determination
R_c^2	Coefficient of determination in calibration
R_p^2	Coefficient of determination in prediction
RMSEC	Root mean square error of calibration
RMSECV	Root mean square error of cross-validation
RMSEP	Root mean square error of prediction
S	Speed of conveyor
s	Second
SD	Standard deviation
SDR	Standard deviation ratio
T_p	Time to peak force
TPHWs	Twenty positive half-waves
TSV	Test set validation
Vis/NIR	Nisible and near-infrared
W	Weight

(NIR) or visible and near-infrared (Vis/NIR) spectroscopy (Cavaco, Pinto, Antunes, Silva, & Guerra, 2009; Lammertyn, Nicolaï, Ooms, De Smedt, & De Baerdemaeker, 1998; McGlone & Kawano, 1998; Shao et al., 2007) or imaging (Lu, 2003; Lu & Peng, 2006; Peng & Lu, 2006) and laser-induced light backscattering imaging (Qing, Ji, & Zude, 2007, 2008), nuclear magnetic resonance (NMR) based methods (Clark, Hockings, Joyce, & Mazucco, 1997) and mechanical-based methods including several techniques such as sonic (Abbott & Massie, 1998; Duprat, Grotte, Pietri, Loonis, & Studman, 1997; Schotte, De Belie, & De Baerdemaeker, 1999), ultrasonic (Mizrach, 2008), vibration excitation (Muramatsu et al., 1999, 2000; Terasaki et al., 2001), hammer impact (Jarén & García-Pardo, 2002) and falling impact (Gutierrez, Burgos, & Moltó, 2007; Lien et al., 2009; Ragni, Berardinelli, & Guarnieri, 2010) methods.

The latter two mechanical methods used for firmness estimation of different fruits have been examined in several researches. With a hammer or forced impact method, a shaped impactor, usually equipped with a piezoelectric accelerometer, is used for either dropping onto the fruits (Jarén & García-Pardo, 2002) or impacting them (García-Ramos et al., 2003). This method has been successfully implemented for the online sorting of avocado according to its firmness with a capacity of 5 fruit s^{-1} (Howarth, Shmulevich, Raithatha, & Ioannides, 2003), classification of peach, pear and apple into two classes at a capacity of 7 fruit s^{-1} (Homer, García-Ramos, Ortiz-Cañavate, & Ruiz-Altisent, 2010) and discrimination of three spherical balls of different materials with a velocity of 6 sample s^{-1} (García-Ramos et al., 2003). Despite the common and numerous applications of this technique for commercial fruit firmness sorting, it is not easy to implement this technique on small size fruits such as dates.

With the falling or free impact method, the fruit is freely dropped onto a force-sensitive surface. The impact response is then analysed in either time or frequency domain (Jarén & García-Pardo, 2002; Lien et al., 2009). The main advantage of falling impact, over hammer impact, is the simpler dropping and sensing mechanism for the on-line estimation of fruit firmness (Lien et al., 2009), especially with respect to small size fruits. However, the response with the falling impact method depends on the fruit mass and it is also more sensitive to the fruit radii of curvature at the point of impact (Jarén & García-Pardo, 2002).

In off-line situations, the falling impact method has been successfully applied for firmness determination of blueberry (Rohrbach, Franke, & Willits, 1982), peach (Delwiche, McDonald, & Bowers, 1987; Gutierrez et al., 2007), pear (Wang, Ying, & Cheng, 2007) and tomato (Lien et al., 2009). On the other hand, in on-line configurations, this technique has been capable of classifying peach and pear into two classes with a capacity of 5.1 fruit s^{-1} (Delwiche, Tang, & Mehlschau, 1989), discriminating peaches into two classes with a capacity of 8 fruit s^{-1} (Gutierrez et al., 2007) and measuring kiwifruit firmness with the optimum speed of 1 m s^{-1} (Ragni et al., 2010).

Regarding date palm fruit, our previous work has shown the potential of NIR spectroscopy in its interactance mode for non-destructive firmness estimation (Mireei et al., 2014). However, the technique is not easy to use for on-line applications and it is also more complicated and expensive than the falling impact method. There have been no other reports implementing other techniques for this purpose.

However, most studies in applying the falling impact test have used some impact indices defined from the impact signal for developing firmness prediction or classification models. The first impact index was presented by Rohrbach et al. (1982) as the ratio of peak force, F_p, to the square of time to peak force, T_p (F_p/T_p^2), in estimating the blueberries firmness. Delwiche et al. (1987) showed that the two impact indices of C_1 (F_p/T_p) and C_2 (F_p/T_p^2) were highly correlated with elastic modulus and penetration firmness of peaches. Lien et al. (2009) introduced new impact indices by taking into account the weight variations among tomato samples and arrived at the classification accuracy of 82.3%. Ragni et al. (2010) used the data points of the entire impact signal as the input to an artificial neural network (ANN) model and predicted the firmness of kiwifruits with a coefficient of determination (R^2) of 0.824 and a root mean square error of prediction (RMSEP) of 5.8 N. However, it seems that there is still a need to improve the accuracy of prediction when using falling impact by assuming an impact signal as a fingerprint of the relevant fruit and implementing simpler and more efficient regression models.