Application of vibration response technique for the firmness evaluation of pear fruit during storage

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Abstract Storage conditions of pear affect its subsequent softening process and shelf life. Measurements of firmness have traditionally been carried out according to the Magness Taylor (MT) procedure; using a texture analyzer or penetrometer in reference texture tests. In this study, a non-destructive method using Laser Doppler vibrometer (LDV) technology was used to estimate texture firmness of pears. This technique was employed to detect responses to imposed vibration of intact fruit using a shaker. Vibration transmitted through the fruit to the upper surface was measured by LDV. A fast Fourier transform algorithm was used to process response signals and the desired results were extracted. Multiple Linear Regression models using fruit density and four parameters obtained from modal tests showed better correlation ($R^2=0.803$) with maximum force in Magness Taylor test compared to the models that used only modal parameters ($R^2=0.798$). The best polynomial regression models for pear firmness were based on elasticity index (EI) and damping ratio (η) with $R^2=0.71$ and $R^2=0.64$, respectively. This study shows the capability of the

LDV technique and the vibration response data for predicting ripeness and modeling pear firmness and the significant advantage for commercially classifying of pears based on consumer demands.

Keywords Multivariate linear regression · Storage · Non-destructive measurement · Laser doppler vibrometer · Firmness

Abbreviations

LDV	Laser doppler vibrometer
EI	Elasticity index
f_n	Resonance frequency
RF_2	Second resonance frequency
f_1 and f_2	Frequencies determined at 3 dB below peak resonance
η	Damping ratio
γ	Density
φ	Phase shift
Hz	Hertz
F_{MT}	Magness Taylor firmness
R^2	Coefficient of determination
PCA	Principal Component Analysis
MLR	Multiple linear regression
ANOVA	Analysis of variance

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Introduction

Food quality and safety is a scientific discipline describing handling, preparation and storage of food in ways that prevent food borne illness (Narsaiah et al. 2011). Firmness is a key factor in deciding whether a fruit will be accepted by the consumer because it is related to postharvest ripeness and storage conditions (Molina-Delgado et al. 2009). Pears continue to ripen after harvest, progressing to a portable

stage and then to a condition where they are unacceptable for fresh consumption (Murayama et al. 1998). Thus, assessment of their maturity during post-harvest storage is very important. As they ripen, many of their properties, such as flesh softness, skin color, fragrance, acidity, and sweetness change. Each of these can be used as a factor for monitoring maturity (Terasaki et al. 2006).

Fruit firmness has traditionally been used as an indicator of maturity and is a function of changes in viscoelastic fruit properties (Terasaki et al. 2001a). Numerous procedures have been proposed for measuring fruit firmness. These Measurements have traditionally been carried out following the Magness Taylor (MT) procedure, using either a texture analyzer or hand-held penetrometer to measure maximum penetration force and other related parameters (reference texture tests). The resistance of fruit flesh to penetration can then be evaluated which it is related to cell wall thickness and the resistance of intercellular bindings (Murayama et al. 1998; Landahl et al. 2003). This measurement is influenced by both the operator and the rate of loading, and sometimes fails to give enough information about the global quality of the fruit or changes related to ripening processes going on within the fruit and samples are damaged during evaluation.

Non-destructive techniques have been widely used to measure firmness of fruits. One technique is based on smooth excitation of the fruit surface by a small hammer and resultant mechanical vibrations can be measured directly by an accelerometer (Langenakens et al. 1997). The drawback of such methods is that for measurement of the induced vibration, accelerometer must be attached to the fruit surface. A number of reports have been published on the application of parameters derived from vibrations in the acoustic range for fruit quality evaluation. Many researchers used this method to evaluate firmness in fruits such as kiwifruits and pears (Abbott and Massie 1998; De Belie et al. 2000). Muramatsu et al. (1997) used the laser Doppler vibrometer (LDV) method for non-destructive fruit testing. This method is advantageous as the LDV detector does not require direct contact with the fruit surface, therefore the vibrational signals of fruit can be measured in real time. The natural frequency of the appropriate mode of vibrations is derived from response signal using fast Fourier transformations (FFT) and used to calculate the fruit firmness $f_n^2 m^{(2/3)}$, where f_n is the second resonant frequency and m is fruit mass (Terasaki et al. 2006; Cooke 1972).

Ripening-dependent changes in texture of kiwifruit, peach and Japanese pear, also some physiological disorders of the tissue of one kind of citrus in various stages of maturity were investigated by laser Doppler vibrometer and phase shift between input and output signals were compared to destructive data of texture measurement (Muramatsu et al. 1999). They used phase shift between the input and output

signals in predetermined frequencies and found significant relationship between force-displacement method and phase shifts for the 1200 Hz and 1600 Hz excitation frequencies. Also, using the above method, experiments were conducted to determine changes of texture in persimmon, apple and kiwifruit during the ripening stage. In a certain range of frequencies (1200 Hz to 1600 Hz), the phase shift as a function of ripeness changed significantly. They also determined resonance frequency, peak height and width of the second resonance peak. Resonance frequency for all of tested fruits was a function of ripening (Muramatsu et al. 2000).

Terasaki et al. (2001b) measured the changes of kiwifruit properties by LDV. They used two factors in their experiments were defined by following formulas:

$$S = f_n^2 m^{2/3} \quad (1)$$

$$\eta = \frac{f_2 - f_1}{f_n} \quad (2)$$

Where $f_{n=2}$ is second resonance peak and m is fruit mass as mentioned earlier and f_1 and f_2 are determined at 3db below the second resonance peak. Results showed a significant relationship between factor S and firmness. Also, factor η correlated well with soluble solids content. Terasaki et al. (2006) measured the elasticity index of pears in different storage periods at low temperature (1°C) and Murayama et al. (2006) showed the correlation coefficients between flesh firmness, measured by a conventional probe method and the elastic index was significantly high. Also, correlation between the elasticity indexes of apple samples with Magness Taylor firmness has been obtained by Motomura et al. (2004).

Postharvest quality evaluation of some varieties of persimmons, pear and melon has been investigated using LDV method and an acoustic vibration technique in order to determine the optimum eating ripeness of them (Taniwaki et al. 2009a, b, c, 2010).

It seems that internal restructure of fruits during ripeness cause changes of the modal properties derived from the vibration response, so that it is possible to develop quality predicting model using modal parameters. Measurement of the internal changes of intact fruits by means of LDV method provides perspective for fruit quality prediction and it also allows insights into physiological processes.

Several authors reported the ability of LDV technique to determine the ripeness changes of pear fruit and other fruits with elasticity index and Muramatsu et al. (1999, 2000) related firmness with phase shift in predetermined frequencies. Thus, the objective of present research is to determine an optimum pear firmness model based on several non-destructive parameters and check the ability of these parameters are extracted of LDV vibration response to track

changes of firmness during storage time into multiple and univariate models. These information would be useful in design and develop non-destructive sorting using LDV technique and comparing with other non-destructive techniques.

Materials and methods

Fruit samples

Pear samples of Dargazi variety (export variety) were used for all experiments. In total, 114 samples were harvested on Sep 24 2010 from a commercial orchard near the city of Qazvin (latitude: 36° 15' N and longitude: 50° 1' E).

Samples were stored for 4 months at a temperature of 1 °C and relative humidity of 85 % throughout the experiment period (Abdolahi 2007). During cold storage, pears ripened and reached a buttery and juicy texture. Every 3 weeks (21 days), 19 fruits were removed from cold storage for testing. They included nondestructive tests performed using a laser Doppler vibrometer followed by reference texture tests (MT test) conducted on the same day.

Nondestructive measurement by laser Doppler vibrometer

The experiment was carried out on a single fruit once every 3 weeks. The device used to determine the vibration response is shown in Fig. 1. Each sample was placed vertically on a vibration-generator and random mode of sinusoidal excitation in frequency range from 0 to 2000 Hz was applied for 6 s. Signals were generated by a power amplifier (BAA120, TIRA, Germany) and signal amplitude was adjusted to prevent the sample from falling off the vibration surface. In order to achieve stability, data was collected on the 200th cycles of sinusoidal excitation.

Vibration response of the sample picked up by the laser Doppler vibrometer (VH-1000-D, Ometron, Denmark) is read by a pulse system (Dynax module, B&K, Denmark).

Fig. 1 Positioning of the sample on the vibration generator

Fig. 2 Procedure of measuring vibration response using laser Doppler vibrometer

The vibration applied to the fruits using the electrodynamic shaker was measured using accelerometer (Model Endevco 4397, Meggitt's Endevco Co, USA) placed close to the sample on the vibrating plate. Vibrational spectrum of each sample was obtained using a fast Fourier transform algorithm in the range of 0–2000 Hz with a resolution of 1 Hz (Fig. 2). Resonance frequencies and damping ratio of the second vibrational mode were monitored using frequency response curves and it was determined through formula (2). Elasticity index was calculated from formula (1) (Cooke 1972; Terasaki et al. 2001a) using the second resonance frequency of the vibrational spectrum f_2 (Fig. 3). The phase shift φ is determined using the real and imaginary values in each frequency range.

Measurement of quality attributes

Due to their destructive nature, firmness measurements were carried out after the Laser Doppler measurement. Magness Taylor firmness was measured as the maximum force needed to penetrate the fruit by 8 mm with a cylindrical probe (8 mm diameter) at a speed of 50 mm/min using a universal testing machine (STM20, Santam Co. Iran). Fruit skin was removed at three locations equally spaced on the circle of

Fig. 3 Typical frequency response spectrum of pear fruit

Fig. 4 Actual firmness values versus those predicted by MLR models

maximum diameter (fruit equator) (De Belie et al. 2000). In each case, maximum penetration force was obtained from a force-deformation diagram. The density of fruit was determined using water displacement method (Mohsenin 1978).

Data analysis

SPSS Software (version16, The SPSS Institute Inc., NC, USA) was used for data analysis. Average firmness was calculated based on measurements on three areas of the equatorial circle of the sample. Experiments were conducted on 114 samples and data was collected on the 200th cycles of sinusoidal excitation. Regression analyses were conducted to determine the coefficient of determination between non-destructive and destructive parameters. Relationship between reference firmness values and a set of parameters derived from vibration response curves was obtained using Multiple Linear Regression (MLR).

Multiple regression method is a common method used for quantitative analysis. Equations relating the behavior of the dependent parameter to the descriptors are developed in the following form:

$$Y_i = \beta_0 + \beta_i \times X_i (i = 1, 2, 3, \dots, n) \quad (3)$$

Where Y_i are the dependent variable; β_0 is the intercept and β_i are the regression coefficients of the independent variable X_i ; while n is the number of independent variables. In the present work a stepwise MLR procedure is applied. A good model should have a high coefficient of determination (R^2) and a low standard error of estimate (Std. Err.). In non-linear regression models, the correlations of reference firmness values with the parameters derived from the vibrational spectra were investigated separately and two models were obtained which will be discussed in the Results and discussion section.

Factor analysis was applied to find which of non-destructive variables was best correlated with the reference

destructive parameter. Then, analysis of variance (ANOVA) was used to determine which of these parameters having high differences in storage time. Non-linear regression modeling was then utilized to develop firmness models.

Results and discussion

Models based on multiple regression analysis (MLR)

The relationship between parameters of vibrational spectra and quality characteristic of fruit was obtained by MLR method. In this assessment, parameters derived from the vibrational spectra were the second resonance frequency RF_2 , elasticity index EI, damping ratio η and phase shift φ . The last three parameters were all derived at the second resonance frequency. The fruit density γ and fruit weight were used in stepwise multiple regression. The appropriate equation for future applications was selected based on the number of criteria such as multiple coefficients of determination (R^2), standard error of estimate (Std. Err.) and number of descriptors in the model. The best multiple linear regression models (MLR) have high R^2 , low Std. Err. as shown below:

$$\text{Firm1} = 262.535 - 0.579 \times \text{EI} - 2.516 \times \text{RF}_2 - 0.333 \times \eta - 3.617 \times \varphi$$

$$n = 114; R^2 = 0.798; \text{Std. Err.} = 12.617$$

$$\text{Firm2} = 881.808 + 3.358 \times \text{EI} - 609.396 \times \gamma - 0.325 \times \text{RF}_2 - 2.191 \times \eta - 0.578 \times \varphi$$

$$n = 114; R^2 = 0.803; \text{Std. Err.} = 12.504$$

Table 1 and 2 show the results of multiple linear regression models Firm1 and Firm2, respectively. Figure 4

Table 1 Results of multiple linear regression model (Firm1) to estimate F_{MT} using non-destructive parameters

Model Firm1	Beta	B	Std. Err.	<i>t</i>	<i>p</i> -Level
Regression summary for dependent variable: F_{MT} ; $R=0.893$; $R^2=0.798$; Adjusted $R^2=0.791$; Std. Err=12.617					
constant		262.535	36.330	7.226	0.0000
EI	-1.583	-0.579	0.093	-6.166	0.0000
RF_2	-0.190	-2.516	1.012	-2.485	0.0144
η	-1.942	-0.333	0.047	-7.062	0.0000
φ	1.029	3.617	0.608	5.950	0.0000

Table 2 Results of multiple linear regression model (Firm2) to estimate F_{MT} using non-destructive parameters and fruit density

Model Firm2	Beta	B	Std. Err.	<i>t</i>	<i>p</i> -Level
Regression summary for dependent variable: F_{MT} ; $R=0.896$; $R^2=0.803$; Adjusted $R^2=0.794$; Std. Err=12.504					
constant		881.808	270.202	3.263	0.0014
EI	0.948	3.358	0.632	5.308	0.0000
γ	-0.110	-609.396	268.996	-2.265	0.0254
RF_2	-1.867	-0.325	0.048	-6.675	0.0000
η	-0.165	-2.191	1.017	-2.153	0.0335
φ	-1.564	-0.578	0.093	-6.182	0.0000

represents actual firmness values versus those predicted by MLR models. In model Firm1, only the vibration parameters were used for determining firmness which yielded a coefficient of determination (R^2) slightly lower than model Firm2, in which both vibrational parameters and density of the fruit have been used. In the second model, stepwise MLR (Firm2) both fruit weight and density were used and the model provided a higher correlation using fruit density. Thus, both models Firm1 and Firm2 were responsive with similar R^2 values; however, Firm1 model is simpler as it does not need fruit density data. It shows that firmness modeling using MLR was independent of fruit density and can be used for firmness prediction based on LDV parameters in future applications.

Previous LDV studies for pear fruit (Terasaki et al. 2006; Murayama et al. 2006; Taniwaki et al. 2009b) and other fruits (Motomura et al. 2004; Taniwaki et al. 2009a, c) mainly considered just elasticity index. Phase shift was used in predetermined frequencies for some fruits (Muramatsu et al. 1999) and damping ratio was used by Terasaki et al. (2001b) in their investigation of kiwifruit. Here, for the first time combination of second resonance frequency, elasticity index, damping ratio and phase shift were used for

developing predictive firmness models, although using mass and density of fruit were not so effective.

Relationship between parameters

In the PCA plot of Fig. 5, the reference parameter related to firmness (Magness-Taylor) which is close to the elasticity index and second resonance frequency shows a clear relationship with the damping ratio (positioned on the opposite side of the axis). In this analysis, 87 % of the total variance between the parameters is explained by a two factor model. Figure 5 shows the loading plot of Factor 1 vs. Factor 2 for the two principal components. Matrix of the correlation coefficients for reference firmness parameter and data from non-destructive test results are shown in Table 3. Non-destructive test parameters EI and η (Table 3) correlated well with the reference firmness parameter F_{MT} .

Univariate models for predicting texture firmness

For non-destructive estimation of firmness in pears, two non-linear models were developed to determine the relationship between Magness Taylor firmness parameters with the parameters obtained from the non-destructive test. These are models that use only one of the non-destructive parameters. Best results were obtained with a polynomial model in which the maximum force, F_{MT} , in Magness Taylor test is represented by a regression pattern of the elasticity index EI. Here, R^2 value is equal to 0.71. Table 4 presents the results of polynomial regression model to estimate F_{MT} using EI.

Fig. 5 PCA plot using all the acquired data. Parameters obtained in non-destructive and destructive test are represented in a space formed by Factor1 and Factor2 of the PCA results

Table 3 Correlation coefficients between F_{MT} and non-destructive parameters

	EI	RF_2	η	φ	F_{MT}
EI	1	0.961	-0.828	-0.861	0.807
RF_2		1	-0.791	-0.904	0.732
η			1	0.711	-0.741
φ				1	-0.675
F_{MT}					1

Table 4 Results of polynomial regression model to estimate F_{MT} using EI

	Beta	B	Std. Err.	<i>t</i>	<i>p</i> -Level
Regression summary for dependent variable: F_{MT} ; $R=0.847$; $R^2=0.717$; Adjusted $R^2=0.712$; Std. Err.=14.562					
EI	1.397	4.801	0.954	5.035	0.000
EI^2	-0.566	-0.048	0.023	-2.040	0.044
constant		-18.955	8.348	-2.271	0.025

Fig. 6 **a** Polynomial model relating F_{MT} to EI. **b** Actual versus predicted firmness values **Table 5** Results of polynomial regression model to estimate F_{MT} using η

Model Firm2	Beta	B	Std. Err.	<i>t</i>	<i>p</i> -Level
Regression summary for dependent variable: F_{MT} ; $R=0.802$; $R^2=0.642$; Adjusted $R^2=0.636$; Std. Err.=16.360					
η	-2.207	-28.444	4.790	-5.938	0.000
η^2	1.454	1.131	0.289	3.911	0.000
constant		196.354	19.106	10.277	0.000

Fig. 7 **a** Polynomial model relating F_{MT} to η . **b** Actual versus predicted firmness values

Fig. 8 Average values of EI and η vs. storage time. Vertical bars represent 0.95 confidence intervals

Also, a point plot of the actual versus predicted values is shown in Fig. 6.

Another regression model was developed to predict firmness, the best form of which was a polynomial relationship between the damping ratio η and the maximum force in the Magness Taylor test (F_{MT}) with a R^2 value of 0.64. Table 5 presents the results of polynomial regression model to estimate F_{MT} using η . Also, a point plot of actual versus predicted firmness values is shown in Fig. 7. In both cases (Figs. 6 and 7), better estimations of F_{MT} were obtained in the polynomial models compared to the linear forms. Other vibration parameters did not show good correlations with maximum Magness Taylor force and their correlations were lower compared to EI and η .

Effect of storage time: analysis of variance

Analysis of variance (ANOVA) was conducted to determine the effect of storage time on firmness of stored fruits in order to examine the sensitivity of vibration testing tools to fruit ripeness trend.

Figure 8 shows the average values of elasticity index (EI) and damping ratio (η) in the early stages after harvest and during storage of pears. It is observed that EI changes drastically in storage time of the fruit. This parameter is useful for keeping track of changes in storage time. Specifically during the first 2 months, analysis of variance showed

that among the vibration parameters, elasticity index (EI) during storage is the best predictive parameter for fruit ripeness having the highest F value. The results of an ANOVA analysis of the non-destructive parameters are shown in Table 6.

This finding agreed with the result reported by Terasaki et al. (2006) and Taniwaki et al. (2009b) that the changes in EI of ‘La France’ pear after storage time decreased and showed a bi-phasic decay. In addition, the declination of elasticity index and growth of damping ratio after harvest reflects metabolic and related structural changes in the fruit, mostly in cell walls (Terasaki et al. 2001b) that are responsible for fruit softening and ripeness after harvest. Therefore, these two parameters have the potential to be utilized for prediction of pear firmness and be employed in developing sorting systems.

Conclusion

In this study, we evaluated the response to imposed vibration over a frequency range of 0 to 2000 Hz and found that transmission of induced vibration of pear fruit changed by the tissue as a function of ripeness. The correlations between reference parameter of destructive testing and modal parameters showed that elasticity index (EI) and damping ratio (η) was more highly correlated with F_{MT} . ANOVA results showed that the elasticity index is a better predictive parameter compared to damping ratio for keeping track of pear changes during storage.

This study showed that if more parameters were used from vibration response, the prediction models will be more precise, as compared MLR models ($R^2=0.803$, 0.794) with univariate models ($R^2=0.71$ and $R^2=0.64$ for EI and η , respectively). Present study suggests that the vibration response spectrum may offer useful information for quality analysis of agricultural products other than parameters was used in this research. However, while the initial observations show that probes such as the LDV allow modeling and firmness evaluation of pears, additional research will be necessary to develop all aspects of this method.

Table 6 F -value and p -level from ANOVA results for non-destructive parameters

Non-destructive parameters	Storage time (Days)	
	F	P
EI	139.140	***
RF ₂	74.497	***
η	45.810	***
ϕ	79.491	***

*** represents significant difference at the 0.001 level

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