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Application of vibration response for the nondestructive ripeness evaluation of watermelons

Abbaszadeh R[1], Rajabipour A[1]*, Delshad M[2], Mahjub M[3], Ahmadi H[1], Laguë C[4]

[1]Faculty of Agricultural Engineering and Technology, University of Tehran, Iran
[2]Faculty of Agricultural Sciences and Engineering, University of Tehran, Iran
[3]Faculty of Mechanical Engineering, University of Tehran, Iran
[4]Faculty of Engineering, University of Ottawa, Canada

*Corresponding author: arajabi@ut.ac.ir

Abstract

The assessment of watermelon ripeness on the basis of its apparent properties, such as size or skin colour, is very difficult as traditional methods have various problems and limitations. These include lack of uniformity, concentration of excitation energy within narrow bands and need for physical contact between a fruit and the measuring device. In this study a new method making use of Laser Doppler Vibrometry technology (LDV) has been applied to evaluate the ripeness of watermelons, without many of those limitations. At first a watermelon is excited by a shaker as vibration generating device within a range of frequencies. At the same time, the vibrating response of the upper side of the fruit is measured by LDV. The device emits a laser beam on a spot above the sample. The beam reflected from that point is received by the LDV and finally the vibration response of the sample is measured and the signal is sent to the computer. Using a fast fourier transform algorithm and the ratio of input to response signals, the frequency response of the fruit sample was processed and the desired results extracted. After the nondestructive tests were completed, the watermelon ripeness was evaluated by means of a destructive method. The sugar and firmness of the samples were measured as ripeness indices. In this study four modal properties were derived and used for developing predictive models to relate the vibration response results with the watermelon sugar and firmness. Interaction models by including the fruit mass were found more accurate than other common multiple models. The nonlinear regression model has five variables as sample mass, first and second resonant frequency and also damping ratios of them. For this model the coefficients of determination and the mean square error for the estimation of the fruit sugar were 0.9 and 0.79 respectively. For the estimation of the fruit firmness, they were 0.89 and 0.035. This study demonstrated feasibility of information which is derived from vibration response curves for predicting fruit ripeness. The vibration response of watermelon using the LDV method is measured without direct contact of the device with watermelon; it is accurate and timely, which could result in significant advantage for the commercial-scale classifying of watermelons based on consumer demands.

Keyword: watermelon ripeness, vibration response, LDV, resonance frequency, damping ratio.
Abbreviation: LDV_laser doppler vibrometer; FAO_food and agriculture organization; EI_elasticity index; TSS_total solvable solid; fn_resonance frequency; m_ mass; f1 and f2_frequencies determined at 3 dB below peak resonance; damping ratio; Hz_hertz; s_second; N_newton; g_gram; MSE_ mean square error; R2_coefficient of determination.

Introduction

According to statistics published by the FAO (2008), Iran ranked third among watermelon producing countries. Watermelon quality during consumption mainly depends on the ripeness of the fruit. Typically optimum quality watermelon fruits for eating feature an appropriate balance among sugar, flavour, colour and texture (Stone et al., 1996). Watermelons are usually harvested from the farm only one or two times according to their weight at harvest. Decreasing labor costs and increasing harvesting speed are the two main reasons that explain this harvesting strategy. This may result in watermelons with varying degrees of ripeness reaching the market. Many consumers dispose of the watermelons that are immature, of poor-quality, or spoiled. However, if it were possible to identify those lower quality watermelons and remove them from the distribution system, this would result into increased consumer satisfaction. The determination of watermelon ripeness on the basis of its apparent properties such as size or skin colour is very difficult. The most common way by which people traditionally determine watermelon ripeness includes knocking on the fruits and assessing the ripeness using the reflected sound. This method is prone to human factor errors as only well-experienced individuals can use it in a reliable way (Stone et al., 1996). The limitations of this method have led researchers to study acoustic methods to determine the watermelon ripeness (Armstrong et al., 1997; Diezma-Iglesias et al., 2004; Farabee et al., 1991; Stone et al., 1996; Xiuqin et al., 2006; Yamamoto et al., 1980). Most of the researchers who have studied the acoustic method were not satisfied with the results of their reports. Acoustic methods present many limitations and problems for watermelon grading at an industrial scale. For example, the location and number of excitations, microphone distance, angle of hitting, and hitter device material can all affect the test results. (Diezma-Iglesias et al., 2004; Taniwaki and Sakurai, 2010) Another potential method for the assessment of watermelon ripeness is the use of

Table 1. The averages of the mass and modal properties of the fruit samples

	Average
Mass (g)	4067.05±1786
First resonance frequency (Hz)	30.9725±6
Damping ratio of first resonance	5.595±1
Second resonance frequency (Hz)	133.915±28
Damping ratio of second resonance	4.7525±1

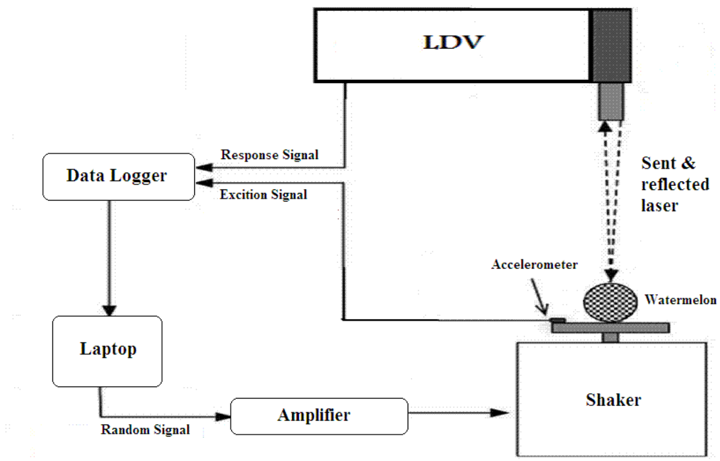

Fig 1. Measuring vibration response of fruits by the LDV method

vibration impulses. Impulses are applied to samples and the generated vibrations are measured by accelerometers. However, one important limitation of this method is the need to paste accelerometers on the watermelon surface, which can be impractical in the grading and sorting industry. The mass of the accelerometer can also be a source of error (Muramatsu et al., 1997; Nourain et al., 2004). In addition, the use of hitting devices results in the excitation energy being focused within narrow specific frequencies and time bands. This particular issue results in limitations for the determination of the exact value of the parameters (Taniwaki et al., 2009). In recent years researchers have been studying a new non-destructive vibration technique using Laser Doppler Vibrometry (LDV) technology to test the quality of some fruits. Muramatsu et al. (1997) have evaluated the texture and ripeness of some varieties of kiwi, peach and pear. They excited samples at different stages of ripeness by means of a 5 to 2000 Hz sine waves. The vibration response at the top of the fruit samples was measured by LDV. Then the phase shift between the input and output signals was compared with the data obtained from the method of force - displacement. A significant relationship between these two methods was found for the 1200 and 1600 Hz excitation frequencies. The ability of the LDV technique for detection of internal defects of some citrus varieties was deemed appropriate (Muramatsu et al., 1999). These authors compared the use of accelerometers and of the LDV system to measure the firmness of some varieties of apple, pear, kiwi, and citrus. They found that the LDV measurements were more accurate than those obtained by means of the accelerometers. Muramatsu et al. (1997) also used the LDV method to determine fruit texture changes during the ripening process. This technique was used for persimmon, apple, and kiwi. For a certain range of frequencies, phase shift as a function of fruit ripeness significantly changed. They also determined that resonance frequencies for all fruits under test were a function of their ripeness (Muramatsu et al., 2000). Terasaki et al. (2001) used LDV to assess the properties of kiwi fruit at different stages of ripeness. Two following factors were considered by them

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

$$\eta = \frac{f_2 \quad f_1}{f_n} \tag{2}$$

Where fn is second peak resonance frequency m is mass of a fruit and f2 and f1 are frequencies determined at 3 dB below peak resonance. The relationship between S and the firmness of kiwi fruit was significantly high. η also showed a good correlation with soluble solids content. (Terasaki et al., 2001). Sakura et al. (2005) conducted some experiments to assess persimmon tissue. They found that the data obtained by the LDV method were significantly correlated with the three variables softness, firmness, and brittleness for persimmon kept in 60% and 100% relative humidity storage. These three variables were evaluated by the sensory method (Sakurai et al., 2005). Murayama et al. (2006) conducted research on pear ripeness by means of the LDV method in which the fruits harvested at different times and under different periods of storage were tested. Their results showed that the correlation coefficients between firmness and elasticity index were significantly high and were dependent on storage duration and harvest time, except for pears that

Table 2. The regression models and their determination coefficients and mean square errors

Multiple models	R^2		MSE	
	TSS	Firmness	TSS	Firmness
Linear with mass	0.78	0.61	1.214	0.086
Linear without mass	0.54	0.49	1.052	0.05
Interaction with mass	0.9	0.89	0.79	0.35
Interaction without mass	0.69	0.77	2.04	0.58
Pure quadratic with mass	0.84	0.8	2.524	0.109
Pure quadratic without mass	0.74	0.7	1.602	0.072

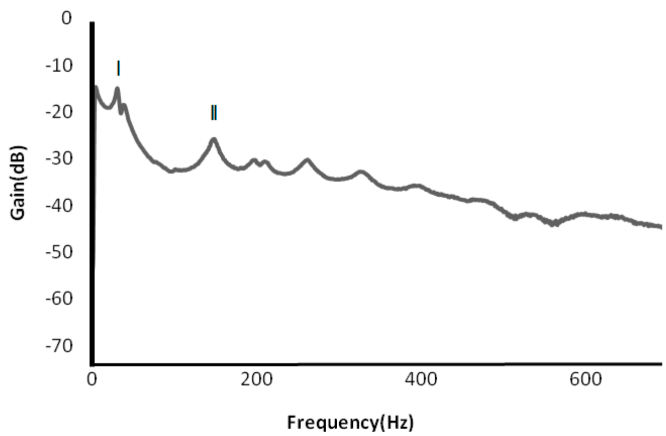

Fig 2. A frequency response spectra

were kept for 4 months in storage temperature of 1°C (Murayama et al., 2006). Taniwaki et al. (2009) also conducted a separate investigation to review change trends in elasticity index (EI) for melon, persimmon, and pear after harvest. They determined the elasticity index from the formula

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

Where fn is the second resonance frequency of the sample obtained using the LDV, and m is the mass of the fruit. The fruit samples were separately assessed for features such as appearance, sweetness, and firmness employing professional people for sensory evaluation. Also the overall fruit acceptability was evaluated. High correlation between the elasticity index and the above mentioned properties was observed. So, the researchers could determine the optimum fruit ripeness time, which is the most appropriate time for eating, according to their elasticity index (Taniwaki et al., 2009). These previous research results indicate that the LDV system could be used for other fruits such as watermelon. The main goal of this research was therefore to study the vibration response of watermelon using LDV system and to develop and introduce a nondestructive method to determine the ripeness of watermelon fruits.

Results

Figure 2 shows the vibration response spectrum for one of the watermelons. The first and second peaks were considered as resonances. The averages of the mass and modal properties of the forty samples are presented by Table1. The common multiple regression models, their determination coefficient, and mean square error are presented in Table 2. Moreover the effect of using sample mass as a variable was studied. After reviewing the linear, interaction and pure quadratic models, the interaction model that including mass was fitted for relating watermelon ripeness index to the results derived from the vibration response curves. For this model the coefficients of determination and the mean square error for the estimation of the fruit firmness were respectively 0.89 and 0.035; for the estimation of the fruit sugar, they were 0.9 and 0.79. The actual and estimated values of the ripeness indices were plotted in Figures 3 and 4 to visually evaluate the performance of the models. The calculated values were determined by selected interaction models. Table 3 shows the numerical values of the interaction regression coefficients of the model.

Discussion

The vibration response was obtained as the ratio of the imposed and perceived signals. It seems that variations of total solvable solids in the fruit cells and internal restructuring of watermelon during ripeness cause changes of the modal properties derived from the vibration response, such as resonance frequency and damping ratio. Because of this phenomenon the first and second resonance frequencies and also their damping ratios can be used as variables in the watermelon ripeness modeling. Earlier studies with the LDV which applied vibration response for other fruits considered only the second resonance (Terasaki et al., 2001; Sakurai et al., 2005; Murayama et al., 2006; Taniwaki et al., 2009) while here for the first time first resonance and damping ratio is used for developing predictive models. Meanwhile similar to previous researches about some fruits (Murayama et al., 2006; Taniwaki et al., 2009), including the mass was effective for watermelon quality modeling. The combination of fruit mass and modal properties causes more precise

Table 3. numerical values of the regression model coefficients

Coefficients*	Units	a) Sugar model	Units	b) Firmness model
a_0	-	131.9064	N	-99.28
a_1	1/g	-0.008	N/g	0.0051
a_2	s	-2.9939	N.s	4.7417
a_3	-	-10.376	N	0.8748
a_4	S	-0.3975	N.s	0.1275
a_5	-	-2.2399	N	8.9479
a_6	s/g	2.09E-04	s. N/g	-2E-04
a_7	1/g	6.25E-04	N/g	0.0002
a_8	s/g	-7.07E-06	s. N/g	3E-06
a_9	1/g	-9.43E-06	N/g	-5E-04
a_{10}	s	0.0549	N.s	0.2628
a_{11}	s^2	0.0104	$N.s^2$	-0.013
a_{12}	s	0.0696	N.s	-0.753
a_{13}	s	0.0336	N.s	-0.07
a_{14}	-	0.2338	N	-0.236
a_{15}	s	-0.0139	N.s	0.1412

* These coefficients are for the interaction model defined in equation 5

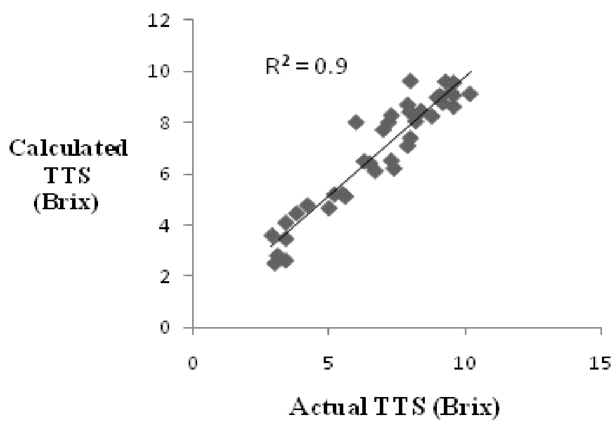

Fig 3. Comparison of actual and calculated values for TSS

models to match watermelon quality and vibration response. First and second resonance peaks have better contrast than others, hence the use of these resonances can increase accuracy for modeling (Fig 2). The average frequency of the second resonance was determined as 134 Hz. Therefore it is possible to reduce the range of frequency of excitation to 0-200 Hz for watermelon although Murayama et al. (2006) excited samples of pears ranging from 0 to 3000 Hz and Taniwaki et al. (2009) subjected persimmon to excitation of 0 to 2000 Hz to find second resonance frequency. This frequency range reduction makes watermelon experiments and data analysis faster. Especially for industrial fruit sorting lines, reduction of time and decrease of energy consumption is an important benefit. This technique does not include the limitations and problems of the acoustic method. This method is also more accurate than the vibration impulse method because of the concentration of the excitation energy within a frequency band at a particular time and no additional mass. The vibration response of watermelons using the LDV method is measured without direct contact between the device and the fruits; it is accurate and timely, which could result in significant advantage for the commercial-scale grading and sorting of watermelons. The method enables well-timed shipment of fruits to the market. Present study suggests that the vibration response spectrum obtained by the LDV may offer useful information for quality analysis other than resonance frequency and damping ratio. The data mining process for feature selection is an approach for extracting the most suitable information. Ebrahimi and Molazade (2010) applied this technique to acoustic spectra in order to conduct almond classification. However, while the initial observations show the feasibility of the laser vibrometery method for ripeness evaluation of watermelons, additional research will be necessary to develop all aspects of this method.

Materials and methods

Measuring vibration response of samples using LDV

In this study 40 watermelons of the Crimson Sweet variety, which is one of the main watermelon varieties for export from Iran, were selected for the experiments. First each watermelon was placed on a shaker vibration plate (Fig. 1).

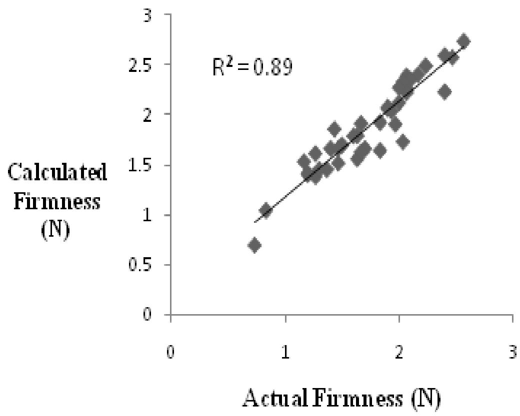

Fig 4. Comparison of actual and calculated values for firmness

The samples were then excited by random signals. These signals were generated by a computer software and applied in a range of frequencies from 0 to 1000 Hz. The signals were amplified by a signal amplifier. The vibration applied to the fruits by the shaking device was measured by accelerometers installed close to the bottom location of the sample on the vibrating plate (Model Endevco 4397). At the same time, the vibrating response of the fruit.s top was measured by a LDV apparatus (Model Ometron VH1000-D, Denmark). The LDV device emits a laser beam to the desired point approximately on the upper side of the sample. The beam is then reflected from that point and returned to the LDV device. The vibration response of the sample, i.e. the velocity change due to moving samples, could then be measured. The accelerometer and LDV signals are transmitted to the computer. Using a fast fourier transform algorithm, the frequency responses of the fruit samples were analyzed by considering the ratio between the response signals and the exciting signals. The desired data was then extracted. Using frequency response curves from the accelerometer and LDV system, the damping ratio and the resonance frequencies of the first two vibration modes were measured. For each resonance peak the damping ratio was obtained from the equation (2).

Watermelon ripeness destructive test

Following the nondestructive testing and weighing of the fruit samples with a digital scale, the ripeness of the watermelon samples was evaluated. To determine the sugar amount, the percentage of total soluble solids (TSS) of samples juice measured by means of a refractometer was taken into account as an index for the amount of sugar in the fruit. To determine the firmness of the fruit, a penetrometer (Model FT327, Aalsmeer – Holland) was used. The forces required to penetrate an 8 mm diameter piston into the internal tissue of a cut melon were measured at three different points. Determination of predictive models Finally using the software, MATLAB 7.6.0 (R2008a), the relationship between the LDV test results and the destructive testing was determined. Determination of the coefficient was considered as a selection criteria of predictive models. Three common multivariate regression models were chosen to fit the experimental results. To investigate the effect of the fruit mass the regression was done first by including the fruit mass as a variable and second by excluding the mass from the model. The general form of the linear, interaction and pure quadratic models for five variables (mass, resonant frequencies and damping ratios) are presented by the following equations, respectively:

$$y = a_0 + \sum_{n=1}^{5} (a_n x_n) \quad (4)$$

$$y = a_0 + \sum_{n=1}^{5} (a_n x_n) + \sum_{n=2}^{5} (a_{n+4} x_1 x_n) + \sum_{n=3}^{5} (a_{n+7} x_2 x_n) + \sum_{n=4}^{5} (a_{n+9} x_3 x_n) + a_{15} x_4 x_5 \quad (5)$$

$$y = a_0 + \sum_{n=1}^{5} (a_n x_n) + \sum_{n=6}^{10} (a_n x_{n-5}^2) \quad (6)$$

Where
y = a) Sugar (Brix, dimensionless); b) Firmness (N)
x_1 = sample mass (g)
x_2 = first resonant frequency (Hz)
x_3 =damping ratio of the first resonant frequency
x_4 =Second resonance frequency (Hz)
x_5 =damping ratio of the second resonant frequency
For the models which were without mass, x_1 wasn't considered as one of the variables and excluded from the models**.**

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References

Armstrong PR, Stone ML, Brusewitz GH (1997) Nondestructive acoustic and compression measurements of watermelon for internal damage detection. Appl Eng Agric13 (5):641-645.

Diezma-Iglesias B, Ruiz-Altisent M, Barreiro P (2004) Detection of internal quality in seedless watermelon by acoustic impulse response. Biosyst Eng. 88(2): 221-230.

Ebrahimi E, Mollazade K (2010) Integrating fuzzy data mining and impulse acoustic techniques for almond nuts sorting. Aust J Crop Sci 4(5):353-358.

Farabee M, Stone ML (1991) Determination of watermelon maturity with sonic impulse testing. ASAE Paper No. 91-3013, St. Joseph, Mich.: ASAE. Published by the American Society of Agricultural Engineers, USA.

Food and Agriculture Organization (FAO); 2008. <www.fao.org> (2010-11-10).

Muramatsu N, Sakurai N, Wada N, Yamamoto R, Tanaka K, Asakura T, Ishikawa-Takano Y, Nevins DJ (1997b) Critical comparison of an accelerometer and a laser Doppler vibrometer for measuring fruit firmness. Horttechnology7;434–438.

Muramatsu NL, Sakurai N, Wada N, Yamamoto R, Takahara T, Ogata T, Tanaka K, Asakura T, Ishikawa-Takano Y, Nevins DJ (1999) Evaluation of fruit tissue texture and internal disorders by laser doppler detection, Postharvest Biol Tec15(1): 83-88.

Muramatsu N, Sakurai N, Wada N, Yamamoto R, Tanaka K, Asakura T, Ishikawa-Takano Y, Nevins DJ (2000) Remote sensing of fruit textural changes with a laser Doppler vibrometer. J Am Soc Hortic Sci 125(1): 120-127.

Murayama H, Konno I, Terasaki S, Yamamoto R, Sakurai N, (2006) Nondestructive method for measuring fruit ripening of 'La France' pears using a laser Doppler vibrometer. J Jpn. Soc Hortic Sci 75:79–84.

Nourain J, Ying Y, Wang J, Rao X (2004) Determination of acoustic vibration in watermelon by finite element modeling. Proceedings of SPIE. The International Society for Optical Engineering 5587(24):213-223.

Sakurai N, Iwatani S, Terasaki S, Yamamoto R, (2005) Evaluation of 'Fuyu' persimmon texture by a new parameter "Sharpness index". J Jpn Soc Hortic Sci 74:150–158.

Stone ML, Armstrong PR, Zhang X, Brusewitz GH, Chen DD (1996) Watermelon maturity determination in the field using acoustic impulse impedance techniques.T Asae, 39:2325–2330.

Taniwaki M, Hanada T, Sakurai N (2009) Postharvest quality evaluation of''Fuyu" and ''Taishuu" persimmons using a nondestructive vibrational method and an acoustic vibration technique. Postharvest Biol Tec 51(1):80-85.

Taniwaki M, Hanada T,Tohro M, Sakurai N (2009) Non-destructive determination of the optimum eating ripeness of pears and their texture measurements using acoustical vibration techniques. Postharvest Biol Tec 51(3):305-310.

Taniwaki M, Sakurai N, (2010) Evaluation of the internal quality of agricultural products using acoustic vibration techniques. J Jpn Soc Hortic Sci. 79 (2):113–128.

Taniwaki M, Takahashi M, Sakurai N (2009) Determination of optimum ripeness for edibility of postharvest melons using nondestructive vibration. Food Res Int 42(1):137-141.

Terasaki S, Wada N, Sakurai N, Muramatsu N, Yamamoto R, Nevins DJ (2001) Nondestructive measurement of kiwifruit ripeness using a laser Doppler vibrometer. T Asae 44:81–87.

Xiuqin R, Yibin Y (2006) Inspection of watermelon maturity by testing transmitting velocity of acoustic wave. Ama, 37(4):41-45.

Yamamoto H, Iwamoto M, Haginuma S (1980) Acoustic impulse response method for measuring natural frequency of intact fruits and preliminary application s to internal quality evaluation of apples and watermelon. J Texture Stud 11:117-136.