Oral Session | Postharvest Machinery

[4-1445-D] Postharvest Machinery

Wed. Sep 4, 2019 2:45 PM - 3:15 PM Room D (4th room)

[4-1445-D-02] A Nondestructive Acoustic Vibration System for Apple Firmness Assessment

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Keywords: Fruit firmness, Excitation device, Test parameters, Vibration characteristics

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A Nondestructive Acoustic Vibration System for Apple Firmness Assessment

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ABSTRACT

Fruit firmness is closely related to the physical structures and mechanical properties, which is an important index at different stages of the food supply chain. In this paper, a loudspeaker-based excitation device was designed and compared with the traditional vibration shaker. The apples were placed on a string bag and driven by the swept sine wave signals ranging from 50 to 2000 Hz. And the response signal of apples was acquired by a laser doppler vibrometer (LDV) which was hung on the top of the excitation units. The test parameters of detection system were optimized in the single factor experiment, and the superior combination of test parameters were as follows: the aperture of sound source was 40 mm, the distance between fruit surface and loudspeaker was 95 mm, and the posture style was that the apple was placed with its stem upward. After the optimization of detection system, six vibration characteristics were extracted from the frequency response function (FRF) to establish the relationship with fruit firmness obtained by the puncture test. The correlation results showed the stiffness of apples was closely related to elasticity index (*EI*) and stiffness coefficient (*SC*), which was considered as a dependent variable in different regression models. Furthermore, the highest correlation coefficient r_p of the prediction set was observed in the BP neural network model by using *EI*, the peak value at f_2 and the peak area as the independent variables (r_p=0.914, RMSEP=0.561 N mm^{-1}).

Keywords: Fruit firmness Excitation device Test parameters Vibration characteristics

1. INTRODUCTION

With the increasing requirement for high-quality fruits, fruit classification and detection are becoming more and more important, which are based on both external and internal quality. External quality indicators mainly contain color, shape, size and appearance quality, while internal quality indicators mainly include chemical compositions (sugar, acidity, vitamin content, inorganic salt, ester, ethylene, etc.), texture and defects. As for the apple, firmness is widely used for its texture or ripeness evaluation, which is closely related to the physical structures and mechanical properties (Li et al., 2011; Pozrl et al., 2010). Accurate detection of firmness is indispensable in fruit supply chain. At harvest stage, firmness is utilized to determine the optimal harvest time and ripeness for edibility. In the grading process, firmness is the basis for classification. In the transportation, firmness is regard as a standard to select proper methods of transportation and packaging. During the storage, firmness helps to confirm storage temperature, humidity and time. As for the sale stage, firmness is used to assess the shelf-life and freshness, which deeply affect consumer purchase behaviors (Zhang et al., 2015). Fruit firmness detection methods can be divided into two classes, including destructive and nondestructive methods. The widely used destructive methods are the Magness-Taylor puncture test, which was deemed to be an industry standard. In the puncture test, a penetrometer records the force-deformation (F/D) curve by penetrating fruit tissue at a certain speed and extracts firmness indexes of fruit flesh based on F-D curve (Camps et al., 2005). However, destructive methods are time-consuming, labor-intensive and local measurement. Thus, many nondestructive techniques have been developed for firmness assessment, such as acoustic vibration (Taniwaki and Sakurai, 2010), spectroscopy (Xing et al., 2006), ultrasonic (Mizrach and Flitsanov, 1999), etc. Among them, acoustic vibration method was commonly used in practice use, since it provides direct measurement of the mechanical and physical properties (García-Ramos et al., 2005; Grotte et al., 2002). Based on existing researches, a series of vibration characteristics were extracted to evaluate the fruit firmness, such as f^2m, $f^2m^{2/3}$ and $f^2m^{2/3}\rho^{1/3}$ (Abbott et al., 1992; Duprat et al., 1997; Schotte et al., 1999). To obtain the acoustic vibration characteristics, many measurement methods and experimental apparatuses were developed (Taniwaki and Sakurai, 2010). In order to not influence the original vibration of the sample, noncontact excitation devices and detection sensors were introduced to nondestructive measurement, such as the loudspeaker and the laser Doppler vibrometer (LDV). Muramatsu et al. (1996) used a small speaker to emit sound wave with frequencies from 200 to 2000 Hz to excite the fruits by an oscillator, and the response signal was acquired by a microphone on the opposite side. Similarly, Kataoka et al. (2016) developed a portable device to detect tomato firmness, which consisted of a smart phone, a microphone and speaker. The smart phone provided the swept sine signal from 20 to 10000 Hz in 1 s to excite fruit by speaker and captured the response signal by a microphone. Besides, the LDV is another alternative non-contact sensor to obtain the vibration velocity of the samples based on the Doppler shift of the laser beam frequency for its merits of noninterference movement, high spatial resolution, high precision and large measuring range (Murayama et al., 2006). In the early time, Muramatsu et al. (1997) applied the LDV system to monitor the firmness of apples, kiwifruits and pears. The results showed that vibration spectrum received by a laser doppler vibrometer had higher precision than the accelerometer method, especially in the frequency band from 800 to 1600 Hz. Lately, Abbaszadeh et al. (2013) developed a LDV system to estimate the firmness of watermelon. In the detection, the watermelon with a reflective film was excited by a mechanical shaker, and the vibration response signal was recorded by the LDV. The results showed that the prediction of stepwise multiple linear regression model (SMLR) based on phase spectrum was better than partial least squares regression model, and the determination coefficient of validation set was 0.9986.

The objectives of this research were to: (i) develop a loudspeaker-based excitation device and compare detection results with the traditional vibration shaker; (ii) to investigate the optimal test parameters in the single-factor experiment, including apple posture style, the aperture of sound source, and the distance between fruit surface and loudspeaker; (iii) to establish the relationships between apple firmness and vibration parameters in different regression models.

2. MATERIALS AND METHODS

2.1 Samples

'Fuji' apples (*Malus domestica* cv. Fuji, produced in Shanxi province, China) were purchased from the local fruit orchard, which has round shape, firm and juicy flesh, rich nutrition ingredients and good storage ability. A total of 48 apples with uniform size and spherical shape were selected and stored in the laboratory at 20 ℃ and 60 %RH. Before the test, each sample was placed at room temperature for 12 h and randomly coded. Then the morphological properties of each sample were measured three times, and average values were calculated for analyses, including the mass (m), height (h) and equator diameter (d). After that, the vibration response signals and the firmness of samples were acquired by the following tests.

2.2 Vibration Response Signal Measurement

The design of the vibration measurement systems was shown in Fig.1, which was similar to the detection system used by Zhang et al. (2014) and Cui et al. (2015) (Fig.2). The system was mainly consisted of a loudspeaker (CS622C, Dayton Enterprises, USA), a microphone (40AE, M+P Enterprises, Germany), a LDV equipment (LV-S01, Sunny Instruments Singapore Pte., Ltd., Singapore), the NI data acquisition unit (USB-4431, National Instrument, Austin, USA), a power amplifier and a PC. In the measurement, the apple with a reflective film was placed on the string bag to vibrate freely. And the loudspeaker produced the swept sine wave signal (frequency range from 100 to 200 Hz in 1 s) to stimulate the apple. The sound signal was recorded by the microphone as the input signal (X_{in}). In the meantime, the LDV was used to acquire the vibration response signal from the fruit surface, which was regard as output signal (X_{out}). These two signals were changed from the time domain to the frequency domain based on Fast Fourier Transform (FFT), and the ratio was the frequency response function (FRF) (Fig.3). Then some vibration characteristics were extracted from FRF, such as the peak value (A), the second resonant frequency (f_2), the peak width at half height (w) and peak area (S=Aw).

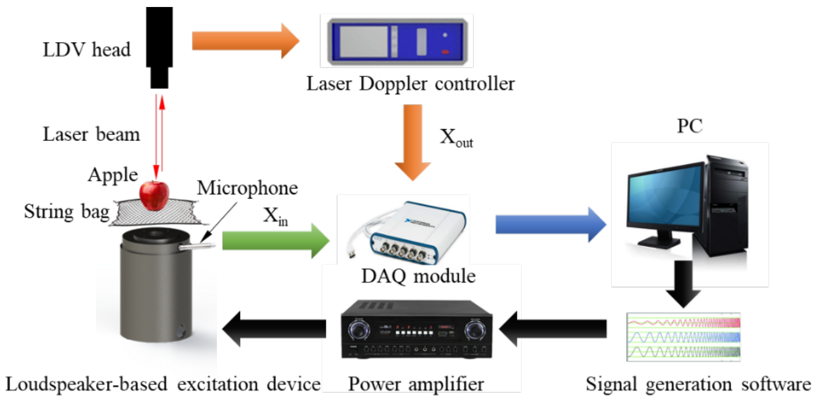

Figure 1. A loudspeaker-based LDV detection system.

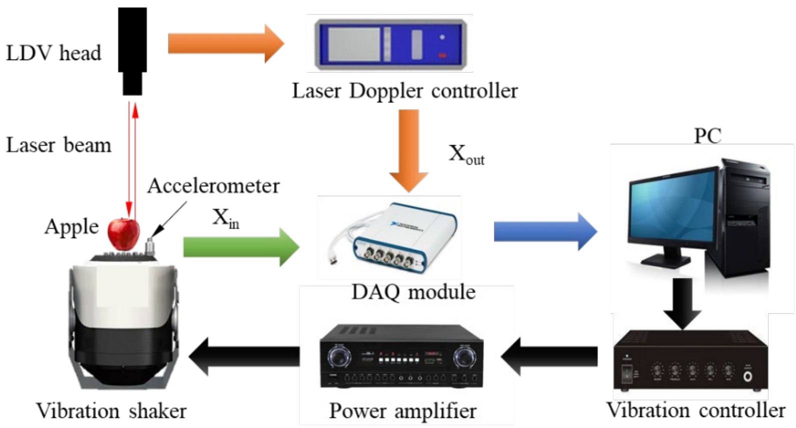

Figure 2. A vibration generator-based LDV detection system.

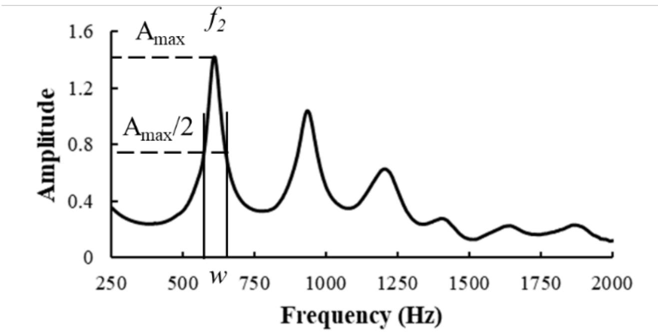

Figure 3. The typical FRF obtained from an apple by the acoustic vibration system.

2.3 Firmness Measurement

The firmness of apples was destructively measured by a standard penetrometer (TA-XT2i, Stable Micro Systems Ltd., England). In this study, three peeled detection points with equal intervals on the equator of the apple were selected. At each site, a flat-tip cylindrical probe (P/5) with a diameter of 5 mm was inserted into the sample. The penetration velocity and depth were 1 mm s^{-1} and 8 mm, respectively. Three firmness indexes were extracted from the force/deformation (F/D) curve, including stiffness (*Stif*, the slope of curve before the rupture point), *MT* firmness (the maximum force) and flesh firmness (*FF*, the mean force at a distance of 2–8 mm) (Fig.4). The average values of each firmness index were calculated and used for following analyses.

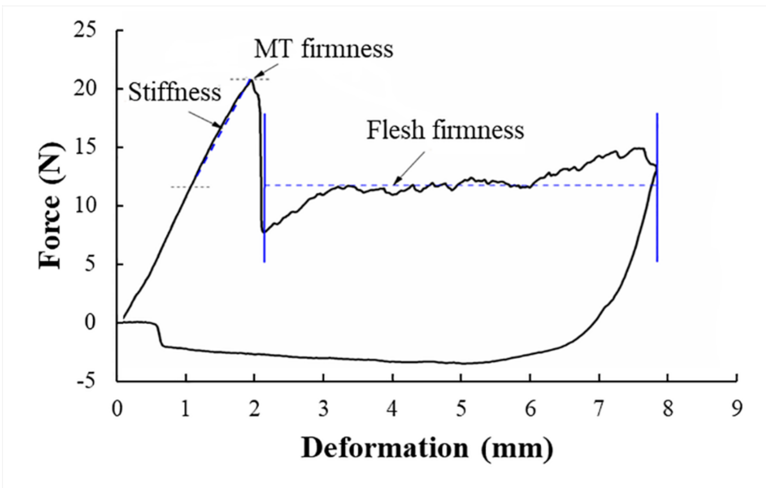

Figure 4. A representative force–deformation curve obtained from the puncture test.

2.4 Statistical Analysis

Correlation analysis was utilized to understand the direction and strength of the relationship between 2 individual variables (Cliff and Bejaei, 2018). In this study, the relationships among the firmness indexes extracted from force/deformation (F/D) curves and vibration characteristics obtained from FRF were assessed with values of the correlation coefficient (*r*), which were calculated through the Eq. (1).

$$r = \frac{\sum_{i=1}^{n}(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i-\bar{x})^2 \cdot \sum_{i=1}^{n}(y_i-\bar{y})^2}} \tag{1}$$

where x_i and y_i are nth measurements of variables X and Y (i=1,2, … , n), and $\bar{x}$ and $\bar{y}$ are the mean values of X and Y.

The repeatability of the vibration parameters was evaluated by coefficient of variation (CV), which was ratio of standard deviation (SD) of repeated measurements and their mean values (Mean). In the study, the value of CV below 10% showed that the detection system had a good repeatability (Wen et al., 2015).

Stepwise multiple linear regression (SMLR) method was a method to select significant independent variables and remove those that are not important based on the variance contribution in a linear regression model to avoid multicollinearity (Wang and Xie, 2014).

The partial least squares regression (PLSR) method was used to diminish the influence of high linear correlation between independent variables. In this study, the PLSR model was established with vibration characteristics from 48 apples. There were 32 and 16 samples in calibration and validation sets, respectively.

Support vector regression (SVR) was a supervised learning method which could be used for nonlinear regression analysis. The main characteristics of this method was to maintain the maximal margin and minimize the error (Liu et al., 2014).

Back propagation neural network (BPNN) was a multi-layer feedforward network trained by error inverse propagation algorithm, which was a supervised learning model. A neural network mainly consists of three parts: input layer, hidden layers, and output layer. Each layer had several neurons which was connected with other layers. The main characteristics were forward signal transmission and error back propagation. In the process of calculation, this method would adjust the network weights and threshold according to the prediction error until the result was close to the desired output (Liu et al., 2010).

3. RESULTS AND DISCUSSION

3.1 Physical Properties of Apples

Forty-eight fresh apples were selected with uniform size and shape in local orchard. The mean values and SD of the physical parameters such as mass, height, and equator diameter of test samples were presented in Table 1. It was revealed that the variations of these parameters were less, which indicated that the differences in their appearance were limited.

Table 1. Physical properties of experimental apples (n=48). (SD: Standard deviation)

Physical parameters	Mass (g)	Height (mm)	Equator diameter (mm)
Mean ± SD	280.06±31.41	79.47±4.28	74.53±3.78

3.2 Comparison of Contact and Noncontact Type Excitation Methods

The loudspeaker was used as a noncontact type device to excite the apple which was placed on a string bag, while the shaker was regard as a contact type device in excitation. The differences in performances of these two devices were compared based on the second resonant frequency (f_2) of 12 apples. Each measurement was repeated three times, and the deviation ratios (D) were utilized to describe the degree of the difference (Fig.5), which were calculated by the Eq. (2). The results showed that the f_2 obtained by shaker-based method was little higher than the loudspeaker-based method. Due to the low values of deviation ratio, it was indicated that there was no significant difference in the second resonant frequency detection by these two excitation methods. However, the intensity of sound wave was relatively low, which may cause the insufficient excitation for large fruit.

$$D = \frac{f_2 - f_2'}{f_2} \tag{2}$$

where f_2 and f_2' were the second frequencies obtained by shaker-based method and loudspeaker-based method, respectively.

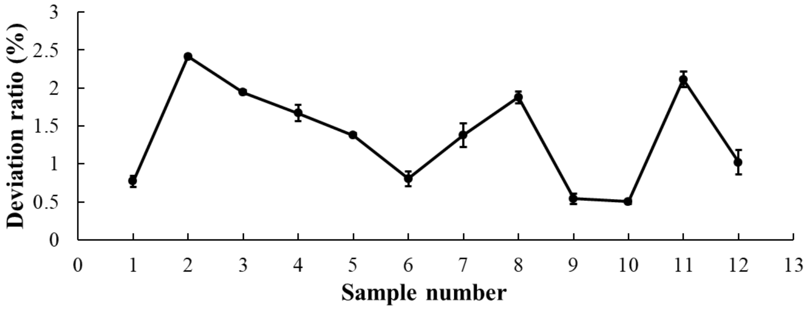

Figure 5. Deviation of the second resonant frequencies of the apple. The bars represent the standard error.

3.3 Repeatability of Vibration Parameters

The repeatability of vibration parameters was represented by the coefficient of variation (CV) of 12 apples (Fig.6). The results showed that the second frequency had the lowest CV value than other indexes. Besides, the peak value had better repeatability than the peak width at half height and the peak area. The CV values of all indexes were less than 10 %, which indicated that the loudspeaker was suitable for excitation in the detection.

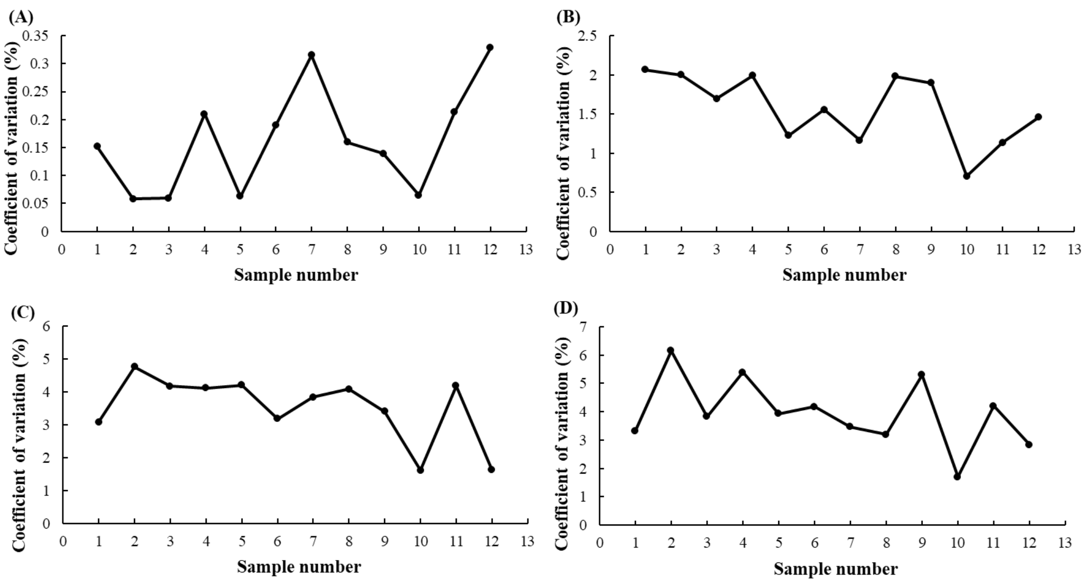

Figure 6. The coefficient of variation of the second resonant frequency (A), the peak value

(B), the peak width at half height (C) and the peak area (D).

3.4 Effects of Test Parameters on Vibration Signal

3.4.1 Different structural parameters

The schematic diagram of the loudspeaker-based excitation device was shown in Fig.7. In general, the intensity of the sound wave was closely related to the diameter of gasket and the distance between fruit surface and loudspeaker. In this section, the signal-to-noise ratio (SNR) was used to evaluate the performance of different structural parameters by single factor experiment.

Figure 7. The schematic diagram of the loudspeaker-based excitation device. (d: the diameter of gasket; h: the distance between fruit surface and loudspeaker)

The three sizes of gaskets were designed in this study, including 20 mm, 30 mm and 40 mm (Fig.8). The SNR values at different diameters of gaskets were shown in Fig.9. It was revealed that the 40 mm gasket obtained the largest SNR value, and there was no significant difference in the other two groups.

Figure 8. The different sizes of gaskets.

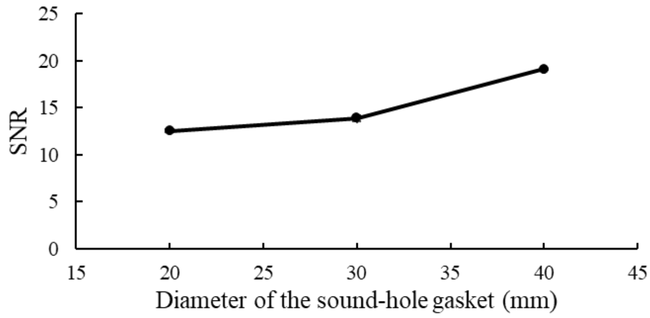

Figure 9. The SNR values of different sizes of gaskets.

The distance between fruit surface and loudspeaker could be adjusted from 95 mm to 155 mm. The SNR values at different distances were shown in Fig.10. The results showed that there was a nearly linear relationship between the SNR values and the distances. And the 95 mm group was found to have the maximum SNR value than other groups. Thus, the optimum size of the gasket and the distance were 40 mm and 95 mm, respectively.

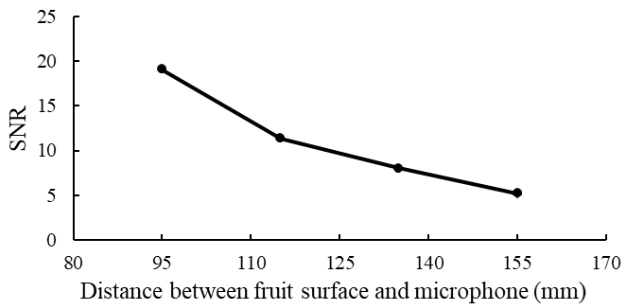

Figure 10. The SNR values of different distances between fruit surface and loudspeaker.

3.4.2 Different Detection Points and Posture Styles

The apple could be placed on the string bag in three different posture styles (Fig.11). In order to evaluate the repeatability of vibration parameters at each posture style, three detection points with equal intervals were selected as a group to compare. The performances of repeatability were represented by CV values (Fig.12). Good repeatability was found in each group of detection points (CV<5%), which indicated that there was no significant difference in different detection points at each posture styles. Besides, posture style B had high CV values in both resonant frequency and peak value.

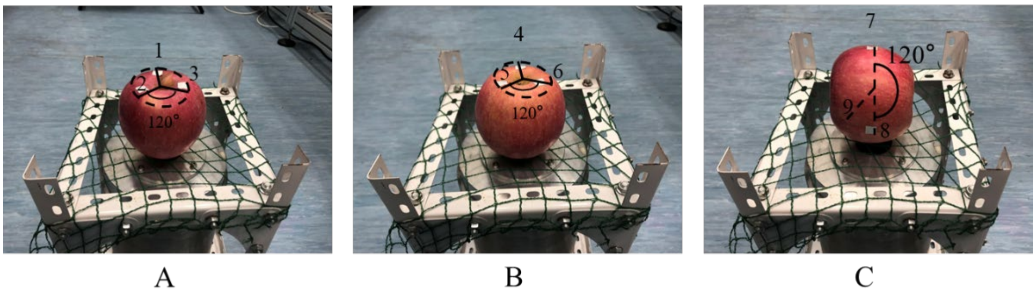

Figure 11. Different detection points and posture styles in detection system. A: the apple stem is upward; B: the apple calyx is upward; C: the apple stem-calyx is horizontal.

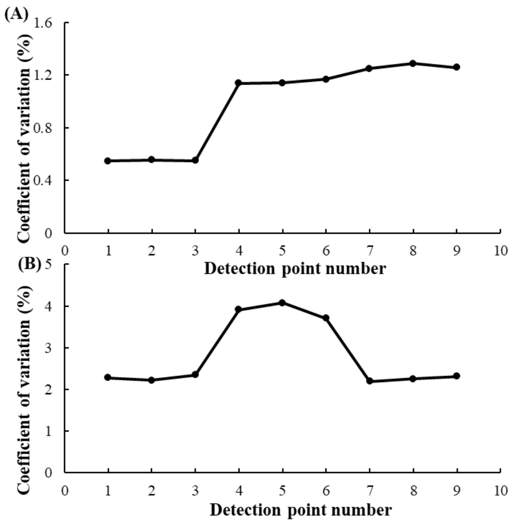

Figure 12. The coefficient of variation of resonant frequency (A), the peak value (B) in different detection points.

Fig.13 showed the SNR values at different posture styles. In general, the posture style A obtained the little higher SNR value than the posture style B. Besides, posture style C had lowest SNR value, which may be caused by unstable placements. Due to the biggest standard error at the posture style B, the posture style A was considered better and selected for the subsequent experiments.

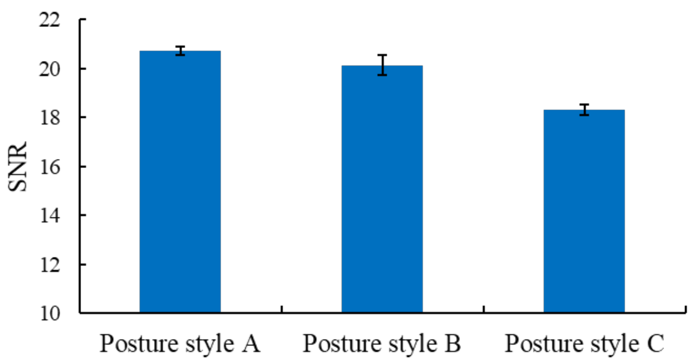

Figure 13. The SNR values of three posture styles. The bars represent the standard error.

3.5 Quantitative Analysis of Apple Firmness

After verification of the optimum test parameters, the vibration response signals of 48 apples were acquired. Four vibration characteristics were extracted from FRF, such as the peak value (*A*), the second resonant frequency (f_2), the peak width at half height (*w*) and peak area (*S*=*Aw*). Then elasticity index ($EI=f_2^2m^{2/3}$) and stiffness coefficient ($SC=f_2^2m$) were calculated to investigate the relationship with fruit firmness. In order to diminish the collinearity effect of these indexes on regression models, the inter-correlations of six variables were represented in Table 2. The results of correlation analysis demonstrated that the cross-correlations among the second resonant frequency, elasticity index (*EI*) and stiffness coefficient (*SC*) were closely correlated ($p \le 0.01$), with *r* values between 0.484 and 0.827 (n = 48). Besides, *w* was strongly correlated with *S* (*r* = 0.771), *EI* (*r* = -0.611) and *SC* (*r* = -0.641). *S* was moderately correlated with *A* (*r* = 0.544), *EI* (*r* = -0.459) and *SC* (*r* = -0.446). The results also indicated that *A* was slightly correlated with the other four variables (*r* = -0.075 to -0.250), except *S*. Strong relationships among the independent variables would lead to the multicollinearity problem in the regression models. Thus, it was necessary to choose appropriate variables to improve the prediction of models. Due to the previous researches, the resonance frequency would be influenced by the object size. Thus, *EI* and *SC* were used to compensate for the difference in fruit size (Abbott et al., 1968; Cooke, 1972). In addition, f_2 and *w* would not be introduced as independent variables in the multiple regression model.

Table 2. Correlation coefficients (*r*) among vibration characteristics (n = 48).

Variable	f_2	*A*	*w*	*S*	*EI*	*SC*
f_2	1					
A	-0.307	1				
w	-0.075	-0.094	1			
S	-0.221	0.544*	0.771*	1		
EI	0.484**	-0.250	-0.611**	-0.499*	1	
SC	0.529**	-0.087	-0.641**	-0.446*	0.827**	1

Asterisks indicate statistical significance: ** significant correlation at the level of 0.01; *significant correlation at the level of 0.05.

The correlations between the firmness indexes obtained by the puncture test and vibration characteristics (*EI* and *SC*) were showed in Table 3. The results revealed that stiffness had the highest correlation with *EI* and *SC*, which was regard as a dependent variable in regression models.

Table 3. Correlation coefficients (*r*) among vibration characteristics and firmness indexes.

Variable	*Stif*	*MT*	*FF*
EI	0.852**	0.534*	0.222
SC	0.629**	0.434*	0.242

Asterisks indicate statistical significance: ** significant correlation at the level of 0.01; *significant correlation at the level of 0.05.

The results of the unary linear regression models were showed in Table 4. All factors (*EI*, *SC*, f_2, *w*, *S*), except *A*, were strongly correlated with fruit stiffness. The best unary regression model for prediction of stiffness was established by using *EI* as an independent variable, whose r_p and RMSEP of prediction set were 0.830 and 0.770, respectively.

Table 4. Statistical results of the unary linear regression models for determining stiffness of apples.

Factors	Regression model	Calibration set		Prediction set	
		r_c	RMSEC	r_p	RMSEP
EI	$y= 4.643\times10^{-5}x+2.768$, F=48.824 (**$P$<0.01)	0.894	0.556	0.830	0.770
SC	$y= 3.961\times10^{-5}x+7.740$, F=13.090 (**$P$<0.01)	0.694	0.628	0.611	1.094
f_2	$y= 0.010x+5.837$, F=8.016 (**P<0.01)	0.556	0.487	0.517	1.182
A	$y= -69.934x+15.082$, F=1.011 ($P > 0.05$)	0.226	1.198	0.210	1.351
w	$y= -0.031x+16.769$, F=11.078 (**P<0.01)	0.573	0.738	0.579	1.126
S	$y= -1.373x+16.295$, F=12.149 (**P<0.01)	0.745	0.540	0.597	1.109

Asterisks indicate statistical significance: ** significant correlation at the level of 0.01; *significant correlation at the level of 0.05.

In order to diminish the collinearity effect of vibration characteristics on a multiple linear regression model, stepwise multiple linear regression (SMLR) was utilized to variable selection. The performances of SMLR models were showed in Table 5. It could be seen that using *EI*, the peak value and the peak area could obtain the better prediction result than another model, and the r_p and RMSEP of prediction set were 0.871 and 0.712 N mm^{-1}, respectively.

Table 5. Statistical results of SMLR model for determining stiffness of the apples.

(I)

Factors	Regression coefficient	Calibration set		Prediction set	
		r_c	RMSEC	r_p	RMSEP
EI	4.042×10^{-5}	0.909	0.474	0.871	0.712
A	22.145				
S	-0.0472				
Constant	4.643				
F=16.210, **P<0.01					

(II)

Factors	Regression coefficient	Calibration set		Prediction set	
		r_c	RMSEC	r_p	RMSEP
SC	2.601×10^{-5}	0.795	0.600	0.701	1.044
A	9.716				
S	-0.934				
Constant	11.352				
F=6.173, **P<0.01					

Asterisks indicate statistical significance: ** significant correlation at the level of 0.01; *significant correlation at the level of 0.05.

The performances of different nonlinear models for prediction of stiffness were represented in Table.6. Compared with the results of the unary linear regression model, PLSR and BP neural network model had the better prediction ability. Besides, SVR model was the worst in calibration set and prediction set. Furthermore, the highest correlation coefficient r_p of the prediction set was obtained in the BP neural network method by using *EI*, *A* and *S* as independent variables (r_p = 0.914, RMSEP = 0.561 N mm^{-1}).

Table 6. Results of quantitative analysis of stiffness by different nonlinear models.

Modeling method	Input variables	Calibration set		Prediction set	
		r_c	RMSEC	r_p	RMSEP
PLSR	*EI*, *A* and *S*	0.904	0.557	0.842	0.754
	SC, *A* and *S*	0.727	0.949	0.688	1.089
SVR	*EI*, *A* and *S*	0.893	0.519	0.801	0.671
	SC, *A* and *S*	0.699	0.627	0.568	0.994
BP neural network	*EI*, *A* and *S*	0.957	0.413	0.914	0.561
	SC, *A* and *S*	0.889	0.617	0.858	0.805

4. CONCLUSION

The loudspeaker-based excitation device was designed and used in the LDV detection system. The test parameters of detection system were optimized based on the results of CV values and SNR values under different test conditions. A better combination of test parameters for vibration response signal measurement were as follows: the aperture of sound source was 40 mm, the distance between fruit surface and loudspeaker was 95 mm, and posture style was that the apple was placed with its stem upward. Based on optimized system, the vibration responses of 'Fuji' apples were acquired, and then six vibration characteristics were extracted, including the peak value, the second resonant frequency, the peak width at half height, peak area, *EI* and *SC*. The correlations between the firmness indexes obtained by the puncture test and vibration characteristics (*EI* and *SC*) were revealed that stiffness had better performance than other firmness indexes, which was regard as a dependent variable in different regression models. Moreover, the best prediction of firmness was observed in the BP neural network model by using *EI*, *A* and *S* as input variables, and the correlation coefficient r_p of the prediction set was 0.914 and RMSEP was 0.561 N mm^{-1}.

ACKNOWLEGMENT

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REFERENCES

Abbaszadeh, R., Rajabipour, A., Mahjoob, M., Delshad, M., Ahmadi, H., 2013. Evaluation of watermelons texture using their vibration responses. Biosystems Engineering 115, 102-105.

Abbott, J.A., Affeldt, H.A., Liljedahl, L.A., 1992. Firmness Measurement of Stored `Delicious' Apples by Sensory Methods, Magness-Taylor, and Sonic Transmission. Journal of the American Society for Horticultural Science American Society for Horticultural Science 117, 590-595.

Abbott, J.A., Bachman, G.S., Childers, R.F., Fitzgerald, J.V., Matusik, F.J., 1968. Sonic techniques for measuring texture of fruits and vegetables. Food Technology 22, 101-112.

Camps, C., Guillermin, P., Mauget, J., Bertrand, D., 2005. Data analysis of penetrometric force/displacement curves for the characterization of whole apple fruits. Journal of texture studies 36, 387-401.

Cliff, M.A., Bejaei, M., 2018. Inter-correlation of apple firmness determinations and development of cross-validated regression models for prediction of sensory attributes from instrumental and compositional analyses. Food research international 106, 752-762.

Cooke, J.R., 1972. An interpretation of the resonant behavior of intact fruits and vegetables. Transactions of the ASAE 15, 1075-1080.

Cui, D., Gao, Z., Zhang, W., Ying, Y., 2015. The use of a laser Doppler vibrometer to assess watermelon firmness. Computers and Electronics in Agriculture 112, 116-120.

Duprat, F., Grotte, M., Pietri, E., Loonis, D., 1997. The acoustic impulse response method for measuring the overall firmness of fruit. Journal Of Agricultural Engineering Research 66, 251-259.

García-Ramos, F.J., Valero, C., Homer, I., Ortiz-Cañavate, J., Ruizaltisent, M., 2005. Non-destructive fruit firmness sensors: a review. Spanish Journal of Agricultural Research 3, 61-73.

Grotte, M., Duprat, F., Piétri, E., Loonis, D., 2002. YOUNG"S MODULUS, POISSON"S RATIO, AND LAME"S COEFFICIENTS OF GOLDEN DELICIOUS APPLE. International Journal of Food Properties 5, 333-349.

Kataoka, H., Ijiri, T., White, J., Hirabayashi, A., 2016. Acoustic probing to estimate freshness of tomato, 2016 Asia-Pacific Signal and Information Processing Association Annual Summit and Conference (APSIPA). IEEE, pp. 1-5.

Li, Z., Li, P., Liu, J., 2011. Physical and mechanical properties of tomato fruits as related to robot's harvesting. Jorunal of Food Engineering 103, 170-178.

Liu, C., Liu, W., Lu, X., Ma, F., Chen, W., Yang, J., Zheng, L., 2014. Application of multispectral imaging to determine quality attributes and ripeness stage in strawberry fruit. PloS one 9, e87818.

Liu, Y.D., Sun, X.D., Ouyang, A.G., 2010. Nondestructive measurement of soluble solid content of navel orange fruit by visible-NIR spectrometric technique with PLSR and PCA-BPNN. LWT - Food Science and Technology 43, 602-607.

Mizrach, A., Flitsanov, U., 1999. Nondestructive ultrasonic determination of avocado softening process. Journal of Food Engineering 40, 139-144.

Muramatsu, N., Sakurai, N., Yamamoto, R., Nevins, D.J., 1996. Nondestructive acoustic measurement of firmness for nectarines, apricots, plums, and tomatoes. Hortscience A Publication of the American Society for Horticultural Science 31, 1199-1202.

Muramatsu, N., Tanaka, K., Asakura, T., Ishikawa-Takano, Y., Sakurai, N., Wada, N., Yamamoto, R., Nevins, D.J., 1997. Critical comparison of an accelerometer and a laser Doppler vibrometer for measuring fruit firmness. HortTechnology 7, 434-438.

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. Journal of the Japanese Society for Horticultural Science 75, 79-84.

Pozrl, T., Znidarcic, D., Kopjar, M., Hribar, J., Simcic, M., 2010. Change of textural properties of tomatoes due to storage and storage temperatures. Journal Of Food Agriculture & Environment 8, 292-296.

Schotte, S., Belie, N.D., Baerdemaeker, J.D., 1999. Acoustic impulse-response technique for evaluation and modelling of firmness of tomato fruit. Postharvest Biology & Technology 17, 105-115.

Taniwaki, M., Sakurai, N., 2010. Evaluation of the internal quality of agricultural products using acoustic vibration techniques. Journal of the Japanese Society for Horticultural Science 79, 113-128.

Wang, A., Xie, L., 2014. Technology using near infrared spectroscopic and multivariate analysis to determine the soluble solids content of citrus fruit. Journal of Food Engineering 143, 17-24.

Wen, Z., Di, C., Ying, Y., 2015. The impulse response method for pear quality evaluation using a laser Doppler vibrometer. Journal of Food Engineering 159, 9-15.

Xing, J., Bravo, C., Moshou, D., Ramon, H., Baerdemaeker, J.D., 2006. Bruise detection on 'Golden Delicious' apples by vis/NIR spectroscopy. Computers & Electronics in Agriculture 52, 11-20.

Zhang, W., Cui, D., Ying, Y., 2014. Analysis of vibration characteristic of 'Huangguan' pears and its relation to firmness during storage. Transactions of the Asabe 57, 1407-1413.

Zhang, W., Cui, D., Ying, Y., 2015. Orthogonal test design to optimize the acoustic vibration method for pear texture measurement. Postharvest Biology & Technology 107, 33-42.