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수박 내부결함판정을 위한 휴대형 압전형 장갑 센서시스템

최동수 이영희 최승렬 김학진 박종민 Koro Kato

Portable Piezoelectric Film-based Glove Sensor System for Detecting Internal Defects of Watermelon

D. S. Choi Y. H. Lee S. R. Choi H. J. Kim J. M. Park K. Kato

Abstract

Dynamic excitation and response analysis is an acceptable method to determine some of physical properties of agricultural product for quality evaluation. There is a difference in the internal viscoelasticity between sound and defective fruits due to the difference of geometric structures, thereby showing different vibration characteristics. This study was carried out to develop a portable piezoelectric film-based glove sensor system that can separate internally damaged watermelons from sound ones using an acoustic impulse response technique. Two piezoelectric sensors based on polyvinylidene fluoride (PVDF) films to measure an impact force and vibration response were separately mounted on each glove. Various signal parameters including number of peaks, energy ratio, standard deviation of peak to peak distance, zero-crossing rate, and integral value of peaks were examined to develop a regression-estimated model. When using SMLR (Stepwise Multiple Linear Regression) analysis in SAS, three parameters, i.e., zeros value, number of peaks, and standard deviation of peaks were selected as usable factors with a coefficient of determination (r^2) of 0.92 and a standard error of calibration (SEC) of 0.15. In the validation tests using twenty watermelon samples (sound 9, defective 11), the developed model provided good capability showing a classification accuracy of 95%.

Keywords : Piezoelectric film sensor, Watermelon, Internal defect, Nondestructive method, SMLR (Stepwise Multiple Linear Regression)

1. Introduction

High value agricultural products must be carefully handled to meet the customer's demands and quality standards. Many methods are available for quality detection and sorting of agricultural products based on external properties such as size, shape, and external defects. However, the quality of fruits is also influenced by their internal factors such as sugar content, structure and smell. In general, the internal quality has been evaluated using destructive methods based on various criteria including saccharic acid ratio, hardness and existence of defect (ripeness, cavity and flesh deterioration) by cutting the fruit open into multiple sections thorough a sampling technique. However, such destructive methods require a lot of time and limit the number of samples to be analyzed. Also although the results obtained from destructive and manual observation methods are accurate, the sample test results may not represent other products

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with different quality levels, thereby requiring the use of a nondestructive method that allows all of the samples to be on-line analyzed at a high sampling intensity.

Internal quality evaluation of watermelon has been normally performed through a manual observation by experts. However, since their evaluations are subjective, a new instrument with some degree of confidence is needed to provide reliable measurement results. Accurate screening of defective watermelon can increase both the trust of consumers and the profits of watermelon growers.

Many researchers have used various nondestructive methods to evaluate the internal quality of watermelon. In particular, the internal quality of watermelon was investigated by hitting the watermelon and examining the sound that occurred with a microphone. Kawamura and Nisimura (1988) used a simple pendulum hung in the air to obtain vibration signals in watermelon. They found that peak frequencies for under-ripened watermelon ranged 170 to 220 Hz when using density spectrum data computed with a FFT (Fast Fourier Transform) whereas the spectrums for well-ripened and over-ripened samples were near 160 Hz and 130~140 Hz, respectively. They also mentioned that the standard for the internal quality distinction of watermelon lied in watermelon size and flesh viscosity. Sasao (1985) measured vibration signals of watermelon during its growing process. He analyzed the acceleration responses of shocks occurring at watermelon surface when it was struck. At the early stage of growth, the vibration waveform showed characteristics of a free vibration. However, at the mature stage it appeared in an irregular form. Chen et al. (1993ab, 1994) developed a theoretical model that can be used for evaluating internal quality of watermelon, assuming that watermelon has a complete elastic structure. By using the model, they could examine three physical conditions, i.e., ripeness degree, internal cavity, and size. In addition, they found that there were high correlations between damping coefficients obtained from free vibration waves and chewing taste values of watermelon, thereby implying that the damping coefficient could be used for evaluating internal quality of watermelon.

Dynamic excitation and response analysis is an acceptable method to determine physical properties of watermelons for quality evaluation. In addition, the development of low-cost, light weight, and flexible piezoelectric film sensors has opened new possibilities for dynamic testing of agricultural products in the packing house. Shmulevich et al. (1996) used a piezoelectric film to measure firmness of agricultural products. The vibration signals were obtained using the piezoelectric sensor attached to a soft large-gapped polyethylene sponge. Kim and Myung (1997) investigated the effects of external shock and damping change on acoustic vibration signals to develop a sensor that could evaluate the degree of ripeness of a watermelon. Also Kim et al. (1998) found that at the ripening stage the waveform became more complicated and low frequency components became strong while frequency components were strongly influenced by two parameters (weight and density).

The overall objective of this research was to develop a glove sensor system composed of two piezoelectric film sensors to screen out watermelon with internal defects. Specific objectives were to: (i) develop a regression-estimated model for the sensor system by relating its time and frequency responses to internal quality of watermelon and (ii) verify the validity of the developed calibration model.

2. Materials and Methods

A. Preliminary Tests

Preliminary tests with a pendulum device were conducted to investigate how the vibration characteristics of watermelons are affected by different types of supports, i.e., polyethylene foam, plastic and soil. Also, to calibrate an impact power sensor consisting of a thin, disk-shaped piezoelectric film transducer, bonded to a similar sized thin plastic disk, watermelon was excited by changing the falling angle of the pendulum from 20° to 90°. The impact power sensor was mounted at the end of the pendulum, in contact with the melon. The impact signals were measured using an oscilloscope at a sampling rate of 5 kHz.

B. Data Collection Using a Portable Glove Sensor System

As shown in Figure 1, two piezoelectric film sensors (CM-01B, 5 volt, MSI Co, USA) were used to measure vibration signals and impact force occurring in the watermelon when it was excited. The piezoelectric sensors were produced with polyvinylidene fluoride (PVDF) films, coated with two thin layers of conductors. The sensing principle is based on the generation of a voltage when a physical change occurs. The sensor offers several advantages, such as thin thickness (28 μm), a wide range of frequency (0.01 Hz ~ 1 GHz), light weight, and low-cost for dynamic testing of agricultural products. In the glove system, the two piezoelectric transducers were separately mounted on each glove to measure acoustic vibration signals (Fig. 2a) and impact force (Fig. 2b) of the watermelon.

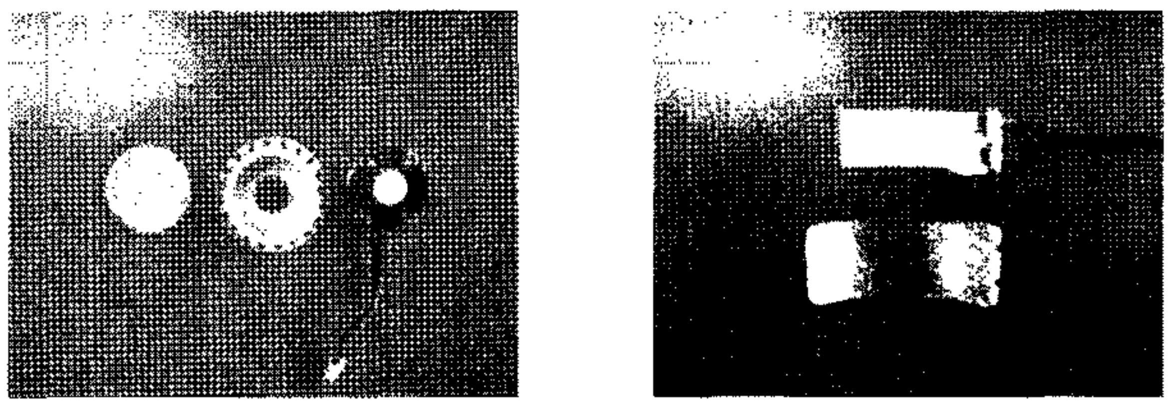

(a) (b)

Fig. 1 Vibration sensor and impact sensor.

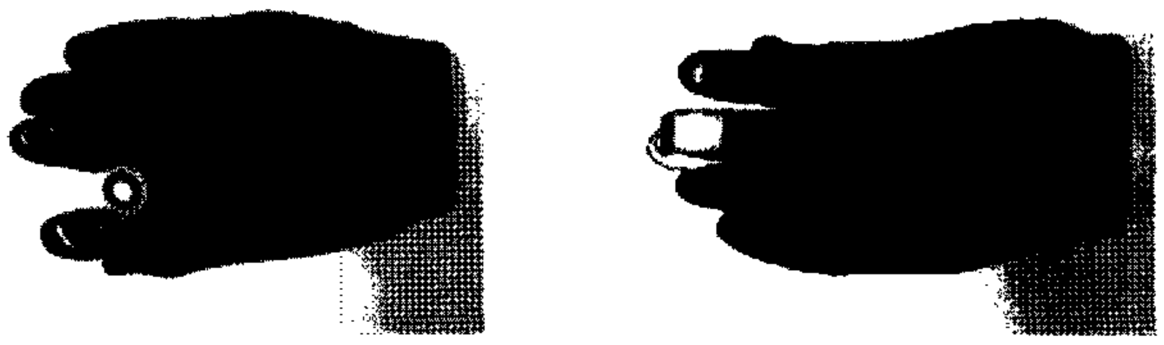

(a) (b)

Fig. 2 The vibration and the impact power sensors set up on gloves.

Two signal processing boards (Fig. 3) were constructed to process data obtained from two sensors, vibration and impact force, respectively. The board included various functions, such as an analog to digital conversion (A/D), signal processing, and data display. In principle, when the watermelon was excited by an impact force, the impact power data stored on the processing board (Fig. 3b) were transmitted to the microprocessor of the vibration sensor (Fig. 3a) via Bluetooth. Figure 4 shows a prototype glove system with two piezoelectric sensors and signal processing boards.

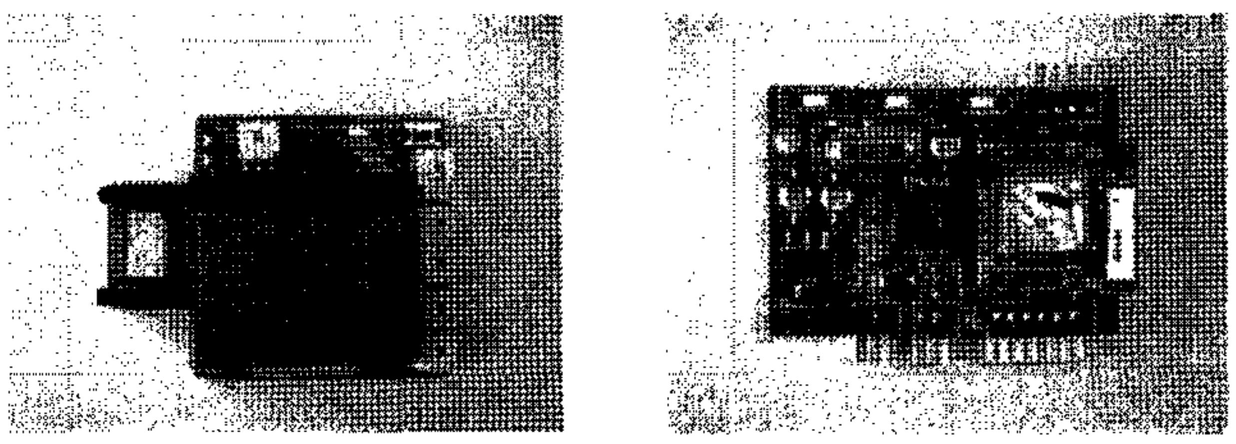

(a) (b)

Fig. 3 Signal processing board for vibration signal and impact power.

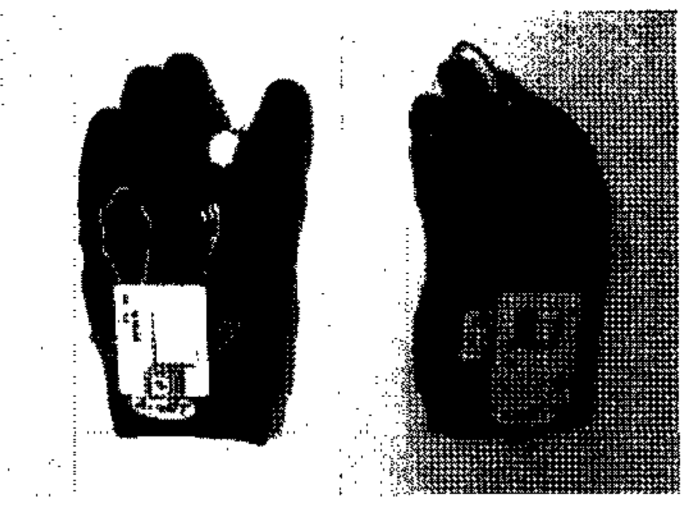


Fig. 4 Watermelon internal quality evaluation gloves.

Watermelons were impacted on the equator side using the right hand glove with the impact power sensor and acoustic signals were then detected on the opposite equator side using the vibration sensor mounted at the left hand glove (Fig. 5). The signals were sampled at a sampling rate of 5 kHz and converted into 1,024 digital signals using an A/D chip in the signal processing board. An NI portable PC-based data acquisition system and a Pentium IV computer were used to download the vibration and impact force data.

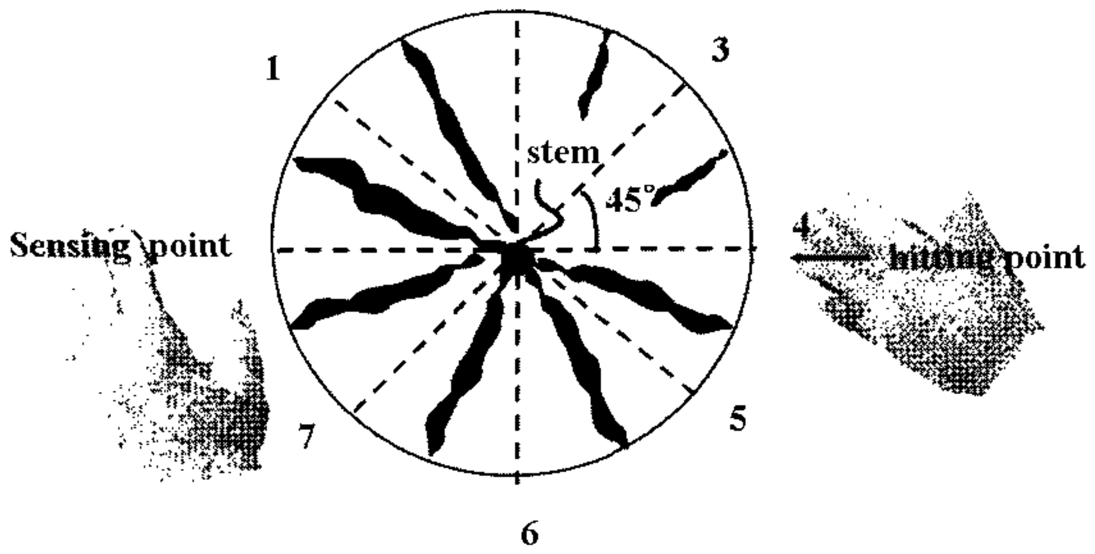


Fig. 5 Data collection using a portable glove sensor system.

To compensate for different impact forces excited by hand, data obtained with the vibration sensor were normalized by multiplying vibration data by a ratio of the impact force measured with the sensor to the power value obtained in calibration. Factors to determine internal quality of watermelon were then examined using the normalized vibration data in time and frequency domains.

C. Development of Calibration Equation and Model Validation

Fifty one watermelon samples (31 and 20 samples for calibration and validation, respectively) were used to develop

Table 1 Criteria for classifying defective watermelons

(a) Blood flesh

Items	sound	1	2	3	4	5
Flesh color* (a value)	Over 22	20~22	18~20	16~18	14~16	Less 14
Area (cm^2)	0	Below 0.5	0.5~3.0	3.0~7.5	7.5~14.0	Over 14.0
Condition of cell wall	sound	before collapse	1/3 collapse	2/3 collapse	collapse	collapse

(b) Inside-cavity

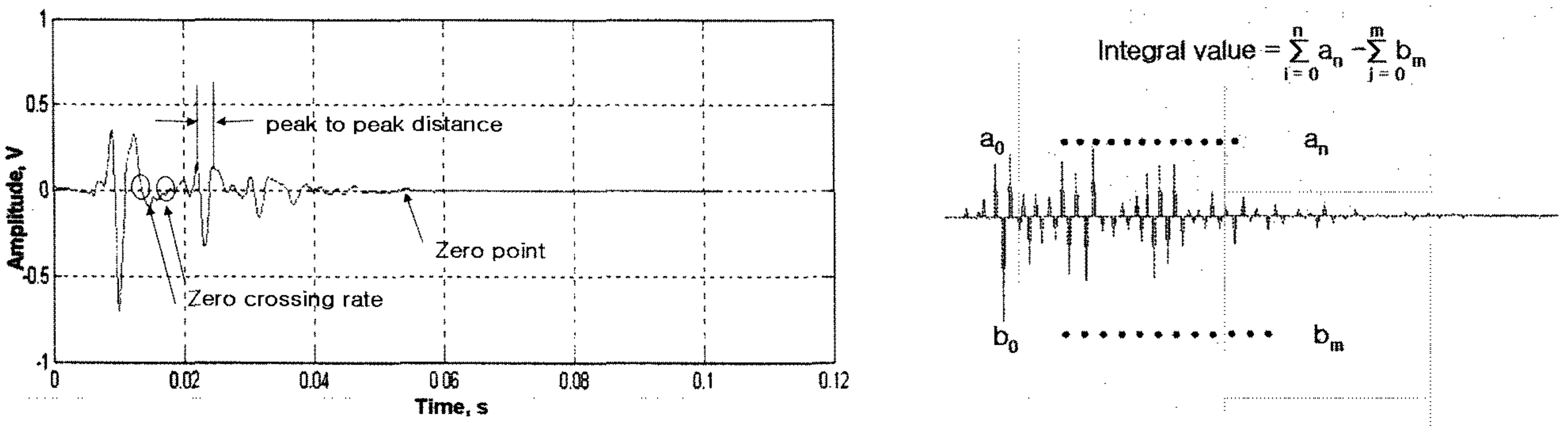
Items	sound	1	2	3	4	5
Width (mm)	0	Below 5	5~10	10~15	15~20	Over 20
Length (cm)	0	Below 1	1.0~3.0	3.0~5.0	5.0~7.0	Over 7.0
Area (cm^2)	0	Below 0.5	0.5~3.0	3.0~7.5	7.5~14.0	Over 14.0

a regression-estimated model and verify its validity. Quality indices based on a destructive method for detecting defective melons with two classifications (blood flesh and inside-cavity) were developed (Table 1), in which the samples were classified into two groups: sound and defective fruits. The flesh color of the watermelon section was measured with a colorimeter and its width and length were measured with the Vernier Calipers. Inside-cavity and blood flesh were classified into 5 grades according to the extent of flesh color, area, width, and length. If score is more than 3 and 2 for inside-cavity and blood flesh respectively, the watermelon was considered to be defective. As a result, twenty five of the fifty one samples were determined to be defective watermelons. For the regression, numerical values were set to be 1 and 0 for sound and defective melons respectively.

Various acoustic parameters of watermelons obtained in time and frequency domains were examined to determine valid factors to develop a regression-estimated model that can detect internally defective melons. In this study, ten parameters were used, i.e., integral values (1 and 2), peak number in time domain, peak to peak distance, standard deviation of peak to peak distance, zero crossing rate, zero point frequency, and energy ratio in frequency domain. Figure 6 shows definitions of parameters used in regression analysis. The zero crossing rate value and zero point frequency were determined by calculating the number of points intersected when amplitudes were zero in time and frequency domains respectively. The integral values 1 and 2 are computed by using amplitudes of peaks in time domain as shown Figure 6b. The integral ranges of integral values 1 and 2 are 80~210 point, 210~400 point within 1024 data points of a vibration signal, respectively

The method employed to build the prediction model was based on multiple linear regression (MLR). To examine the effectiveness of the prediction model, root mean square error (RMSE), bias, and standard error of prediction (SEP) were calculated using the following equations.

$$RMSE = \sqrt{\frac{\sum(\hat{x}_i - x_i)^2}{N}} \tag{1}$$



(a) (b)

Fig. 6 Parameters used in regression analysis.

$$Bias = \frac{\sum_{i=1}^{N}(\hat{x}_i - x_i)}{N} \tag{2}$$

$$SEP = \sqrt{\frac{\sum_{i=1}^{N}(\hat{x}_i - x_i - Bias)^2}{N-1}} \tag{3}$$

where

$\hat{x}_i$: predicted quality index obtained by MLR regression

x_i: actual quality index determined by destructive methods

N: number of samples

Stepwise multiple linear regression (SMLR) in SAS was used with sets of the ten independent variables that were highly correlated to find the subset of independent variables that can provide the best description of the independent variable.

3. Results and Discussion

A. Time and Frequency Responses Under Different Support Conditions

Time and frequency responses of watermelon placed on three different support types to pendulum impact are shown in Fig. 7. The acoustic waveforms in the time and frequency domains were almost the same, thereby implying that there was little difference among three different supports in terms of signal acquisition.

B. Responses of watermelon to impact at different falling angles of pendulum

Figure 8 shows the responses of watermelon to impact when the falling angles of the pendulum were changed. The impact signals increased with increasing the falling angles, showing a polynomial relationship between the sensor output and falling angle (Fig. 9):

$$y = 40.8x^{0.3343} \quad (R^2 = 0.9924) \tag{4}$$

where

x : Sensor output (V)

y : Falling angle of pendulum (degree)

C. Comparison of Acoustic Signals Between Sound and Defective Watermelons

Figure 10 shows a comparison between typical vibration signals in time and frequency domains obtained from sound and defective watermelons with blood flesh. There was a clear difference between two samples in terms of acoustic impulse response. In the time domain, the wave attenuation occurring with the normal watermelon was regular and slow whereas the defective watermelon showed a relatively rapid and sharp attenuation of the acoustic signal. In the fre-

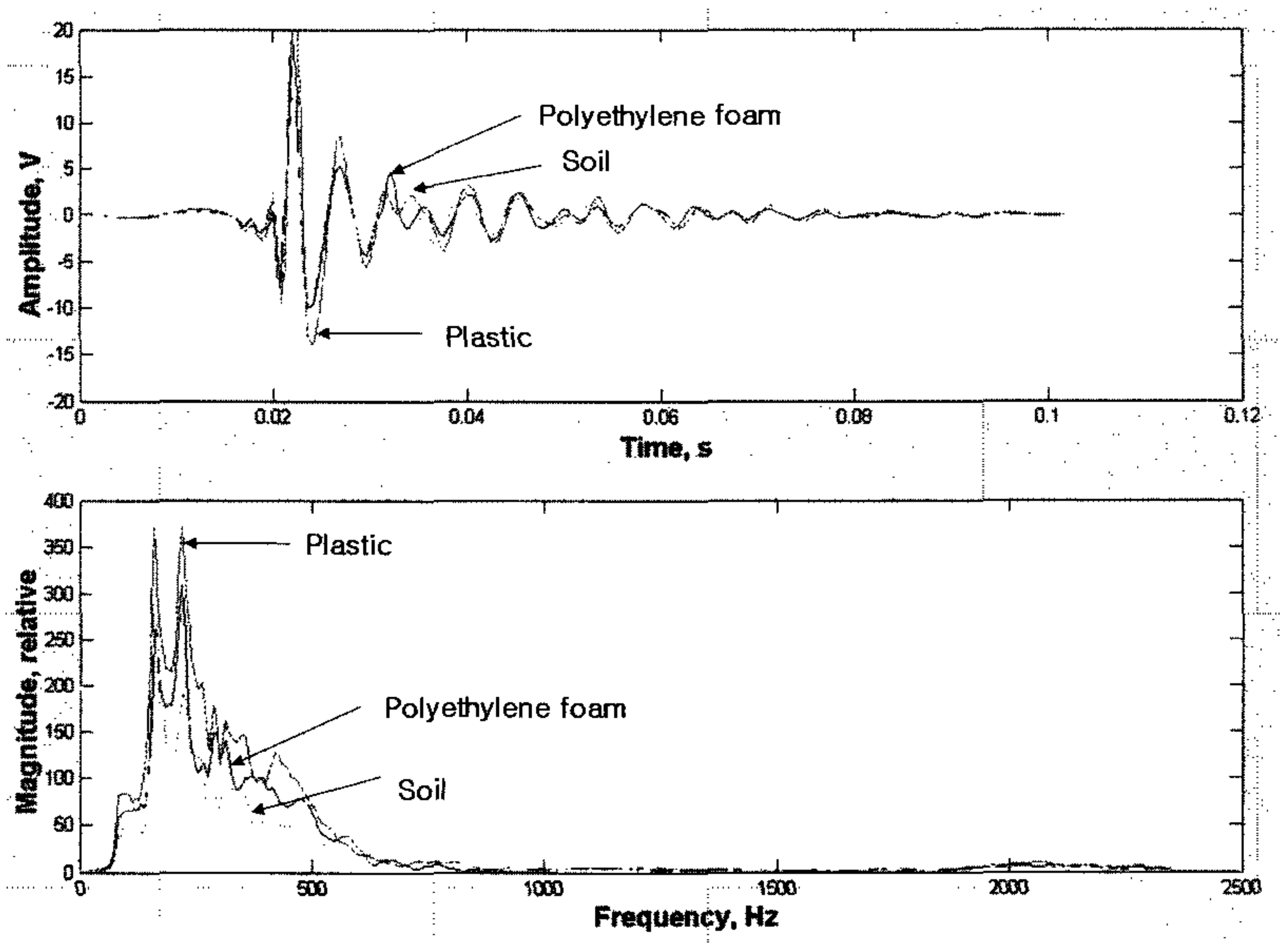


Fig. 7 Time and frequency signal responses of watermelon placed on three different support types, i.e., polyethylene form, plastic, and soil to pendulum impact.

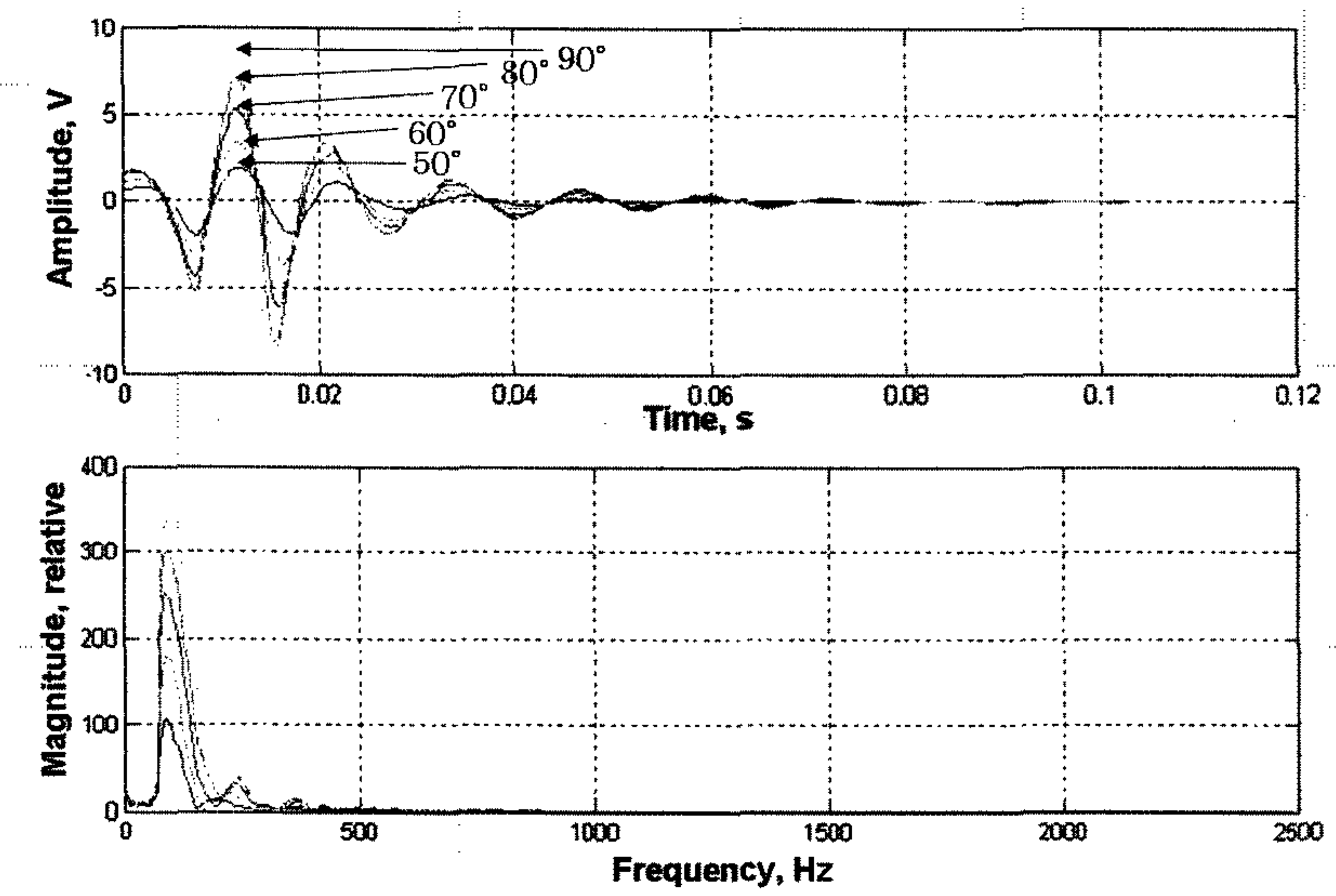


Fig. 8 Time and frequency signal responses of watermelon when the falling angle of the pendulum was changed.

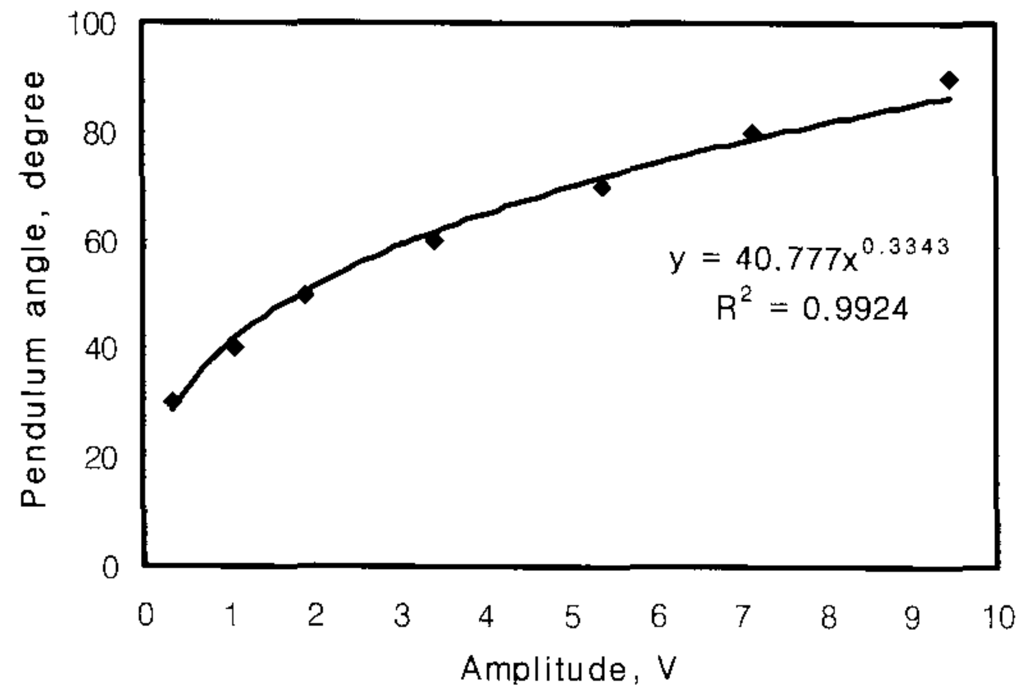


Fig. 9 Relationship between the signal amplitude of the impact power and the falling angle of the pendulum.

quency domain, the range of frequency response for the normal watermelon with peak magnitudes (within 500 Hz) was wider than that for the defective watermelon (within 300 Hz), implying that high frequency components (>300 Hz) did not exist in the defective fruit.

D. Correlation between Quality Index and Acoustic Parameters

Figure 11 shows relationships between sound and defective watermelons in terms of various acoustic signal value

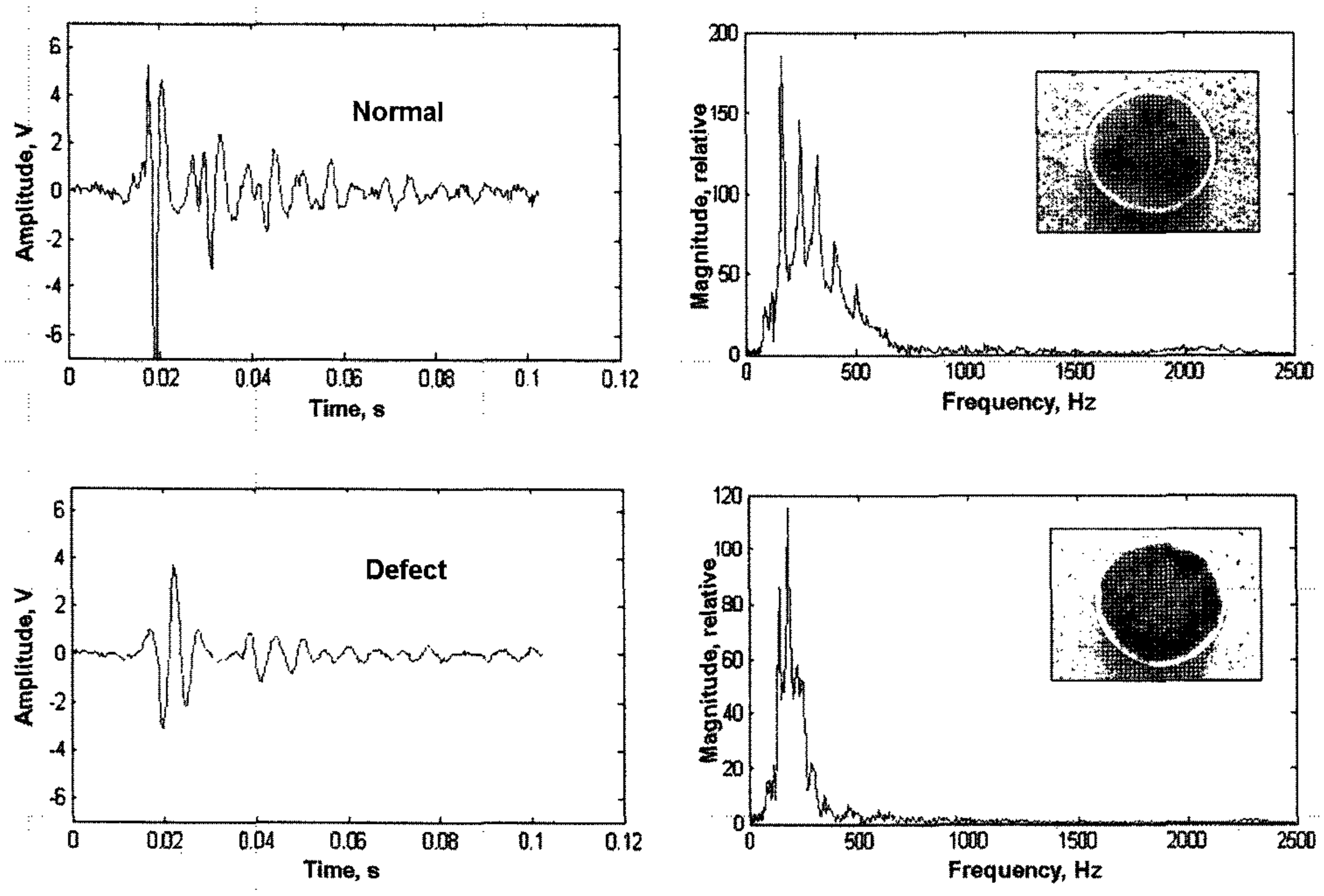


Fig. 10 Comparison between typical sound and defective watermelons in time and frequency domains.

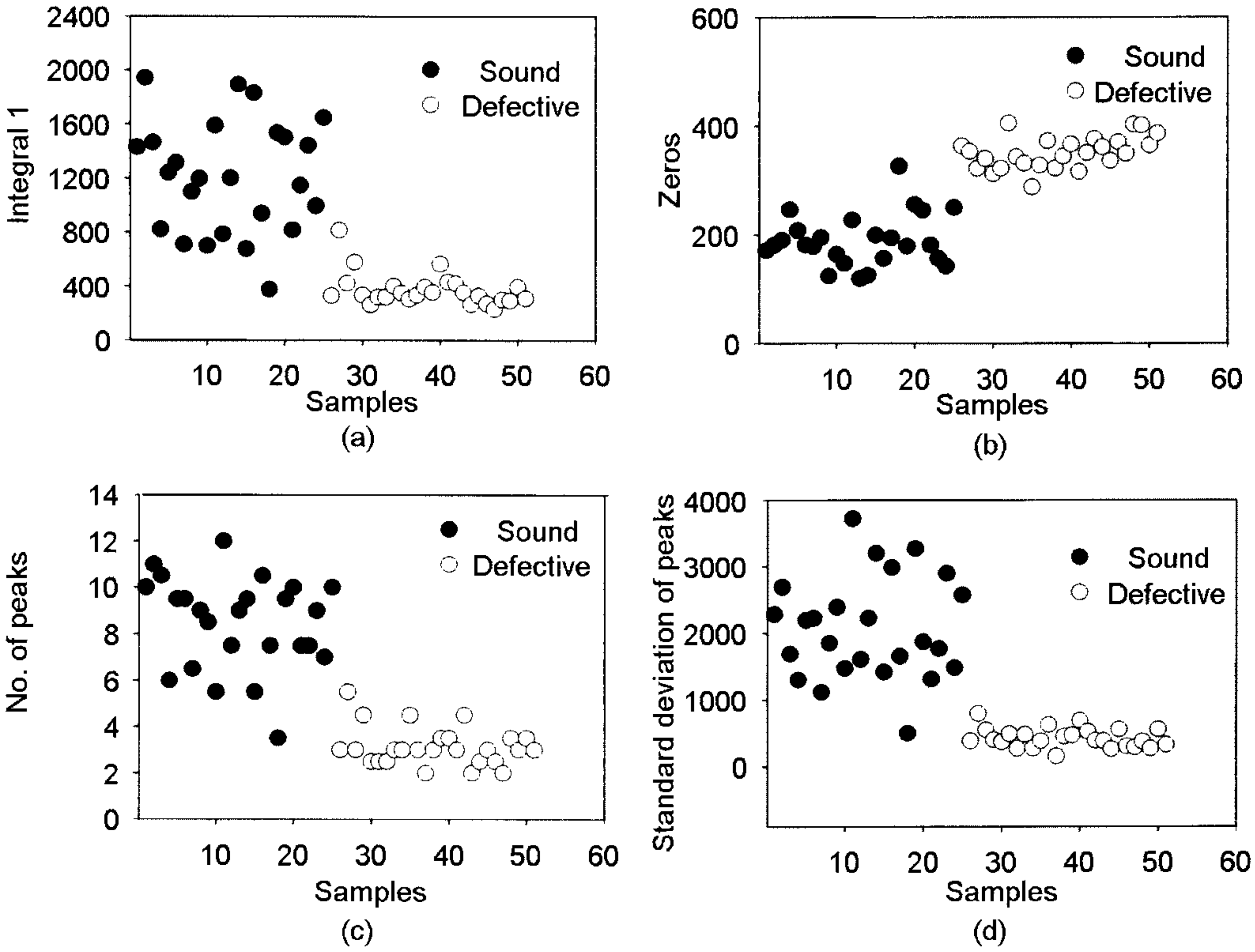
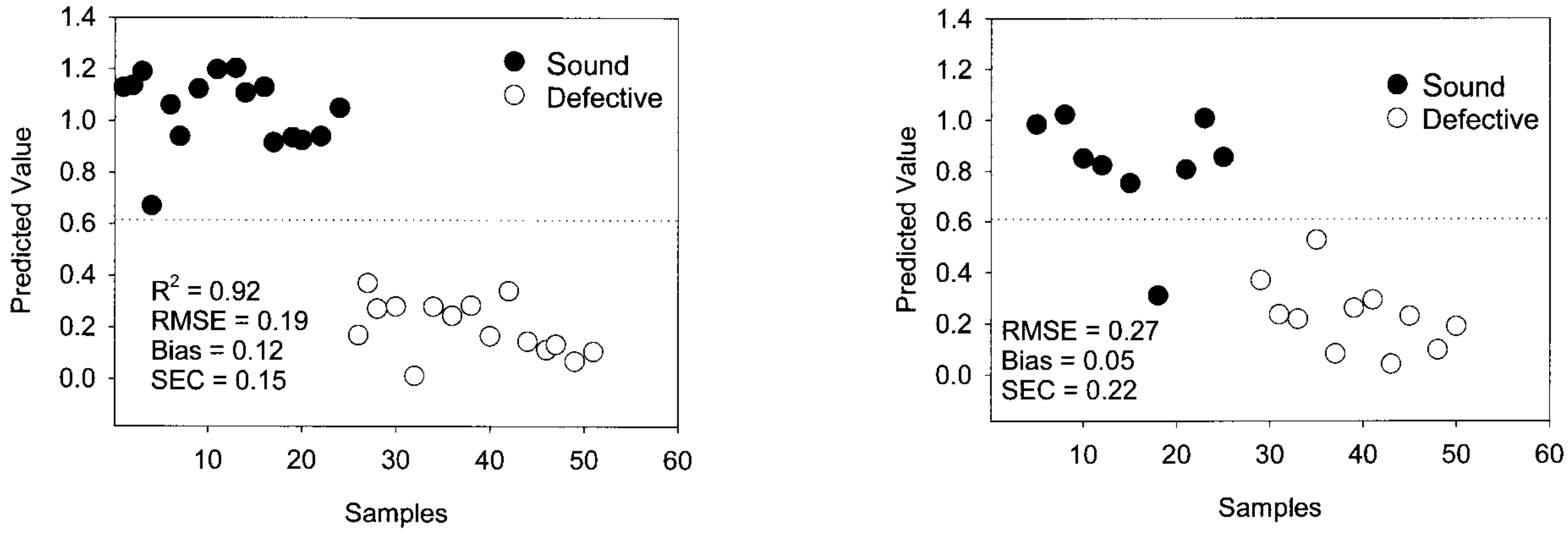


Fig. 11 Correlations of sound and bad watermelons in terms of integral 1 (a), zeros (b), number of peaks (c) and standard deviation of peaks (d).

indices. It was shown that sound and defective watermelons could be divided into two different groups when using the four parameters, thereby implying that the four parameters were highly correlated to quality index. In particular, the integral value 1, number of peaks, and standard deviations of peaks were negatively proportional to quality index whereas zeros value was positively proportional to quality index. Similarly, the other parameters were highly correlated to quality index (Pearson coefficients of correlation of >0.8).

E. Development of Prediction Model and Model Validation

Equation 5 and Figure 12 (a) show the results of the SMLR regression calibration, where three parameters, i.e., zeros value, number of peaks, and standard deviation of peaks were selected as usable factors in effectively predicting the quality index of watermelon. The SMLR-based regression model fit the data very well with a coefficient of determination of 0.923 and a standard error of calibration



(a) Calibration

(b) Validation

Fig. 12 Investigation of predicted quality indices obtained from SMLR regression model in calibration and validation.

(SEC) of 0.15.

$$Y = 1.04 - 0.003Zeros + 0.08885N\_Peak - 0.00012554SD\_Peak \; (R^2 = 0.923) \quad (5)$$

where

Zeros : Number of zero point (dimensionless)
N_Peak : Number of peak (dimensionless)
SD_Peak : Standard Deviation of distance of peak - peak (dimensionless)

The validation of the developed SMLR calibration model was conducted using 20 watermelon samples. Among the total 20, nine samples were sound and eleven samples were defective. As shown in Figure 13b, the model provided good prediction capability showing the RMSE value of 0.27 and Bias of 0.05. Among the twenty samples, only one sample was incorrectly classified (a classification accuracy of 95%).

4. Summary and Conclusions

This study was conducted to develop a portable glove sensor system for detecting internal defects of watermelons. Two piezoelectric sensors based on PVDF films for the measurements of impact force and vibration response were separately mounted on each of a pair of gloves. Valid signal factors were determined based on SMLR analysis by examining ten signal parameters in time and frequency domains that can be used to distinguish defective watermelons from sound watermelons. The following conclusions could be drawn from the study:

(1) In a comparison between typical vibration signals obtained from sound and defective watermelons with blood flesh, in time domain, the wave attenuation occurring with the normal watermelon was regular and slow whereas the defective watermelon showed a relatively rapid and sharp attenuation of the acoustic signal. In frequency domain, the range of frequency response for the normal watermelon with peak magnitudes (within 500 Hz) was wider than that for the defective watermelon (within 300 Hz), implying that high frequency components (>300 Hz) did not exist in the defective fruit.

(2) The impact signals obtained with the piezoelectric film sensor increased with increasing the falling angles, showing a polynomial relationship between the sensor output and falling angle. Acoustic signal parameters examined in the study were highly correlated to quality index determined based on destructive methods, showing Pearson coefficients of correlation of >0.8.

(3) When using SMLR analysis in SAS, three parameters, i.e., zeros value, number of peaks, and standard deviation of peaks were selected as valid factors in effectively predicting the quality index of watermelon. The SMLR-based regression model fit the data very well with a coefficient of determination of 0.923 and SEC of 0.15. In validation, the model provided good prediction capability showing the RMSE value of 0.27 and Bias of 0.05. Among the twenty samples, only one sample was incorrectly classified (a classification accuracy of 95%).

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