FRUIT DENSITY AS AN INDICATOR FOR WATERMELON HOLLOW DETECTION USING HELMHOLTZ RESONANCE

H. Xu, H. Chen, Y. Ying, N. Kondo

ABSTRACT. *The density of watermelon was found to be related to the internal hollow of watermelon and can be used for nondestructive quality evaluation. Obtaining density directly has long been a problem, and researchers have used a variety of methods to determine the volume and then deduce the density. In a Helmholtz resonance system, the resonant frequency has a close relationship with the effective volume of the resonator. The objective of this study was to develop a watermelon volume measurement system using the principle of Helmholtz resonance and then determine the density to classify normal and hollow watermelons. Based on single-factor and orthogonal tests, the optimal parameters of the measurement system were revealed to be 10 s testing time, 220 mm distance from the microphone to the resonator port opening, and 120 mm height of the loudspeaker above the port opening. A total of 176 watermelons, separated into a calibration set (119) and a validation set (57), were measured using this system. The resonant frequency and actual volume measured by water immersion were modeled with linear, quadratic, and negative quadratic regression models, and then binary logistic and support vector machine (SVM) methods were used to identify watermelons with or without hollows using the density values estimated by the original, theoretical, linear, quadratic, and negative quadratic models as input variables. The binary logistic method based on the density values estimated by the negative quadratic model showed the best performance in predicting hollow watermelons, with an overall correct percentage of 82.5%. It was confirmed that Helmholtz resonance showed a great potential for measuring the volume and internal quality of watermelon.*

Keywords. *Density, Helmholtz resonance, Internal hollow, Nondestructive detection, Volume, Watermelon.*

Fruit density is one of the important quality indices for agricultural products. It has long been used as an estimator of soluble solids content (SSC) (Ting and Blair, 1965; Kato, 1997; Sugiura et al., 2001; Jordan and Clark, 2004) and starch content (Hoffmann et al., 2004). Fruit density has also been used to separate fruits with freeze damage (Wardowski et al., 1998), insect damage (Forbes and Tattersfield, 1999), internal desiccation (Miller, 1993), hollow heart (Kato, 1997), and watercore (Throop et al., 1989).

By the definition of density, it is necessary to first determine the volume and mass and then use $\rho = m/V$ (where ρ is density, m is mass, and V is volume) to determine the density. The mass can be obtained by electronic balance with an accuracy of 0.1 g. However, it has long been a challenge to obtain fast and accurate volume measurement. There are two traditional methods for measuring volume: the gas displacement method and the liquid displacement method based on Archimedes' principle. The liquid displacement method is one of the most common and simplest methods, but agricultural products or foodstuffs may be damaged when they were immersed in liquid. The gas displacement method does not damage food seriously, but both of these two methods take quite a long time to perform.

Over the past few decades, different measurement systems have been developed for non-destructive determination of volume. The optical ring sensor system developed by Gall (1997) can be used to estimate the volume of fruits at high speed (up to 2 m s^{-1}) when measuring elongated product such as cucumber or zucchini (Moreda, 2004), with a root mean squared error (RMSE) of 26 mL and root mean squared percentage error (RMSPE) of 5.8% for volume estimates of zucchini. Kato (1997) devised a capacitance system for measuring watermelon volume based on the fundamental relationship between volume and capacitance measured between an ellipsoid and an outer cylindrical casing. This method yielded an RMSE of 26 mL and an RMSPE of 0.4% with correct watermelon orientation and at a speed of 0.22 m s^{-1} (about 0.4 fruits per second). Jarimopas et al. (2005) developed a lower-cost capacitance system to analyze the effects of parameters such as the outer casing diameter, sample shape, and angular displacement of the sample on the volume measurement and obtained good results, with an error of 1.24% for watermelon, 4.56% for large cucumbers, 3.28% for wax gourds, and 3.19% for guava with their longitudinal axes aligned with the axis of the cylindrical casing. Omid et al. (2010) used an image

Submitted for review in December 2013 as manuscript number FPE 10560; approved for publication by the Food & Process Engineering Institute of ASABE in June 2014. Presented at the 2013 ASABE Annual Meeting as Paper No. 131619931.

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Vol. 57(4): 1163-1172 ISSN 2151-0032 DOI 10.13031/trans.57.10560

processing technique to measure the volume and mass of citrus fruits such as lemons, limes, oranges, and tangerines. The coefficients of determination (R^2) for these fruits were 0.962, 0.970, 0.985, and 0.959, respectively. Other studies have used 2-D or 3-D machine vision technology to measure the volume of samples (Kanali et al., 1998; Forbes and Tattersfield, 1999; Lee et al., 2001; Blasco et al., 2003; Hoffmann et al., 2004; Hryniewicz et al., 2005).

Recently, a new, high-precision, non-invasive technique for volume measurement using Helmholtz resonance was proposed. In a Helmholtz resonance system, the resonant frequency has a close relationship with the effective volume of the chamber (cavity) of the resonator. Ichimiya et al. (1993) used Helmholtz resonance theory to predict sample volumes. Nishizu and Ikeda (1995) applied Helmholtz resonance technology to measure the volumes of agricultural products. The volumes of grapes, apples, and adzuki beans were predicted with R^2 values of 0.968, 0.968, and 0.992, respectively. Nishizu et al. (2001) improved the detection system to realize on-line detection. The volumes of wood blocks, metal blocks, and boiled rice were used in the measurement tests. The predicted volumes agreed very well with the actual volumes, with R^2 values of 0.99, 0.99, and 0.97 at conveyor speeds of 15, 30, and 45 mm s^{-1}, respectively. Ohnishi et al. (2008) combined an electronic scale and Helmholtz resonance to measure the density of kiwifruit. They achieved good correlation with a reference method, with an R^2 value of 0.9254 and standard error of prediction (SEP) of 0.0019 g cm^{-3}. Webster (2010) developed a Helmholtz resonator to measure the volume of solids, liquids, and particulate samples and developed two distinct new methods: the resonant hunting technique for rapid determination of frequency, and the Q profile shifting technique for successful volume measurement with environmental sound level and temperature drift compensation, which improved the accuracy of the system, reaching 0.1% of full scale.

Hollow heart in watermelon is caused by accelerated growth, usually under growth conditions of ample water and warm temperatures. In previous studies, acoustic impulse technology was a common method used to detect hollow heart in watermelon (Kouno et al., 1993; Diezma-Iglesias et al., 2002, 2004; Noh and Choi, 2006). Kato (1997) found that the density of watermelon was correlated with the degree of hollow heart. When the density was between 0.938 and 0.95 g cm^{-3}, there were some small holes but they had no influence on fruit quality. Between 0.934 and 0.938 g cm^{-3}, there were some narrow cracks and small holes around seeds. Below 0.934 g cm^{-3}, there were cavities and soft flesh, and over-ripe porous tissue appeared. The lower the density, the larger the cavity was.

This study aims to investigate a new method, i.e., Helmholtz resonance, to predict the volume of watermelons and then determine the density to classify normal and hollow watermelons. To determine the optimal parameters of the Helmholtz resonance system, single-factor and orthogonal tests were conducted. Combined with different volume-prediction models, binary logistic and support vector machine (SVM) methods were used and compared to find the optimal method for classifying normal and hollow watermelons.

HELMHOLTZ RESONANCE SYSTEM

THEORY OF HELMHOLTZ RESONANCE

Figure 1 shows a simple ideal resonator, which consists of a chamber (cavity) and an opening port (neck). When air is driven into the cavity by an external force, the pressure in the cavity increases. When the external force disappears, the higher-pressure air in the cavity flows out. However, this surge of air flowing out tends to over-compensate, due to the inertia of the air in the port, and the cavity is then left at a pressure slightly lower than the outside pressure, causing air to be drawn back in. This process repeats, with the magnitude of the pressure changes decreasing each time. This process resembles a mass (the air in the port) attached to a spring (the air in the cavity). Helmholtz resonance is a phenomenon of air resonance in a cavity that was first discovered by Helmholtz (1885), who established the relationship of the resonant frequency to the volume of the cavity and size of the port, as follows:

$$f_0 = \frac{C}{2\pi}\sqrt{\frac{S}{V\left(l+l_e\right)}} \tag{1}$$

where

f_0 = resonant frequency of the resonator without an object in the cavity

C = velocity of sound in air

d = internal diameter of the port

S = cross-sectional area of the port

V = static volume of the cavity

$l+l_e$ = transmission length of the air in the port, where l is the actual length of the port, and l_e is the compensation value. Helmholtz (1885) determined that l_e = 1.5r, and Webster (2010) gave a new length extension term as follows:

$$l_e = 0.6r + \left(\frac{8}{3\pi}\right)r \tag{2}$$

where r is the radius of the port.

When there is an object in the cavity, the object's volume can be determined by equation 3:

$$f_P = \frac{C}{2\pi}\sqrt{\frac{S}{(V-W)(l+l_e)}} \tag{3}$$

where f_p is the resonant frequency of the resonator with an object in its cavity, and W is the volume of the object.

From equations 1 and 3, W can be deduced as equation 4

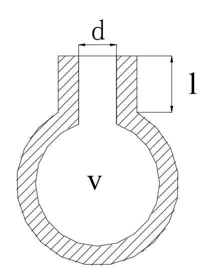


Figure 1. Simple ideal resonator.

(Nishizu and Ikeda, 1995):

$$W = V\left[1-\left(\frac{f_0}{f_P}\right)^2\right] \qquad (4)$$

Equation 4 eliminates the uncertain compensation value (l_e) and sound velocity (C), which minimizes the effect of variable temperature on the measurement accuracy. In addition, the volume has a negative quadratic relationship with frequency.

System for Watermelon Volume Detection

A watermelon volume detection system was designed using Helmholtz resonance theory and consisted of a sound signal source, an amplifier, a loudspeaker, a resonator, a microphone, a data acquisition module, and data analysis software, as shown in figure 2.

Resonator

The resonator was manufactured with a chamber of 350 mm length and 250 mm internal diameter (the length:diameter ratio should be less than 1.5; Selamet et al., 1995), a single port of 300 mm length and 89 mm internal diameter, and a bottom end plate (fig. 2). The chamber and bottom end plate were separable so that a watermelon could be placed inside the resonator. After placing a watermelon on the bottom end plate, a screw was used to raise the bottom end plate, and the chamber and bottom end plate were fastened together. Any air leaks between the two parts could cause variability of the resonant frequency; thus, the chamber and bottom end plate were sealed with an O-ring. A small tray was fixed on the bottom end plate to prevent the watermelon from moving. All parts were made of stainless steel to reduce the effects of ambient temperature and noise.

Microphones

Two sound pressure microphones (INV9206, China Orient Institute of Noise and Vibration) with a frequency range of 20 Hz to 20 kHz, sensitivity of 50 mV Pa^{-1}, and consisting of an ICP pre-amplifier and a prepolarized electret, instead of expensive externally polarized power supplies (www.pcb.com/MicrophoneHandbook) were used to collect sound information. Microphone A was mounted in the port to record the Helmholtz resonant signal caused by the resonator, and microphone B was placed outside the port and near the loudspeaker to record the loudspeaker sound level. This allowed a comparison of the frequency spectrum of each microphone when collecting information.

Data Acquisition Module

A data acquisition (DAQ) module (USB-4431, National Instruments, Austin, Tex.) was used to connect the microphones to a personal computer (PC). The DAQ module consists of four analog input channels for dynamic signal acquisition from microphones and a single analog output channel. Each input channel has a maximum sampling rate of 102.4 kS s^{-1} (1000 samples per second), which can be automatically adjusted to the real-time sampling rate with built-in anti-aliasing filters.

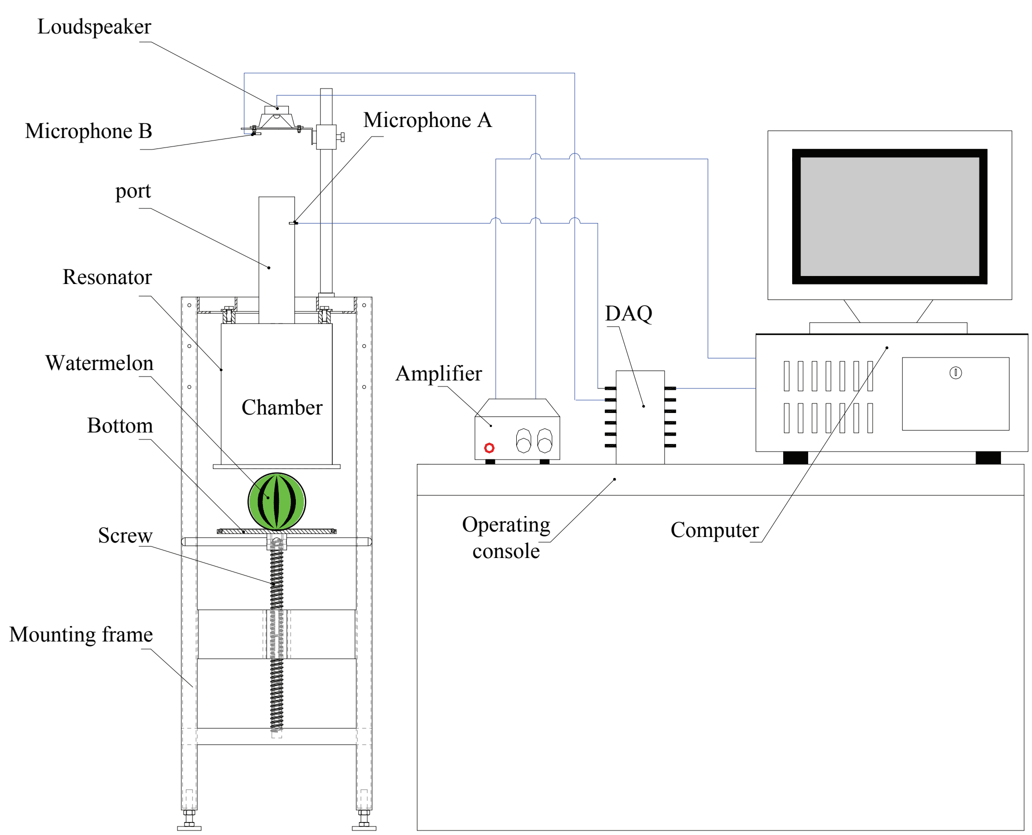


Figure 2. Schematic diagram of the Helmholtz resonance system.

Software

A user-friendly Windows-based software program, Data Acquisition and Signal Processing (DASP, China Orient Institute of Noise and Vibration), was used to acquire and process data. DASP contains tools specifically for time-domain and fast Fourier transform (FFT) analysis, as well as detailed analytical tools for post-processing results. The time versus intensity of the acoustic signal was determined first, and then FFT of the signal was performed to determine the frequency spectrum using DASP. In this study, sampling at 2560 Hz for 8192 points resulted in a resolution of 0.3125 Hz for the FFT spectrum, which is higher than that mentioned in a previous study (Diezma-Iglesias et al., 2004) to ensure precise volume detection.

Sound Signal Source

In order to quickly locate the resonant frequency, broadband noise should be used (Chanaud, 1997; Webster, 2010). Pink noise consists of random frequencies of equal power (Webster, 2010). In this experiment, pink noise was used as the sound signal source to drive the Helmholtz resonance; thus, the resonant frequency could be observed as a peak in the frequency domain. In the preliminary test, chirps were used as the driving sound signal source, but the resonant frequency could be easily masked by the chirps.

Other Components

A loudspeaker with a power of 50 W was installed above the resonator port. A hi-fi stereo audio amplifier with a maximum output power of 180 W was used to connect the loudspeaker and PC.

Materials and Methods

Watermelon Data Sets

During the testing season, we selected 176 ‘Kylin’ watermelons grown in the Yuhang district, Hangzhou, China, and harvested in May 2013, 40 to 50 days after flowering. The farmer helped us cultivate some of them with hollow heart. The watermelons were placed at room temperature for 24 h for equilibration to reduce the effect of temperature on prediction accuracy, and then cleaned, numbered, and weighted with an electronic scale (APTB 457A, Shenzhen Jintaier Instrument Co., Ltd., Guangdong, China) before signal acquisition.

Resonant Generation and Detection

In this study, free Test Tone Generator software (v3.92), which runs on a PC with a sound card as an audio signal generator, was used to generate pink noise, which was fed to the loudspeaker through the amplifier. DASP enabled the two microphones to measure the sound signals from the resonator and loudspeaker. The data were recorded and analyzed using FFT to obtain the frequency spectrum and find the Helmholtz resonant frequency using DASP. The watermelon volume could then be obtained using equation 4.

As mentioned by Webster (2010), there are no ideal methods for determining suitable parameters for a Helmholtz resonance system. Thus, we first investigated three factors: the position of microphone A, the position of the loudspeaker, and the testing time. As shown in table 1, six levels of the microphone A position (where h is the distance from microphone A to the port opening), six levels of the loudspeaker position (where H is the height of the loudspeaker above the port opening), and six levels of testing time (t) were used to conduct single-factor tests. At each level of each factor, six replication measurements were conducted using the same watermelon to measure the Helmholtz resonant frequency. The variance (σ^2) of the measured Helmholtz resonant frequency was used as the assessment criterion: σ_1^2 was calculated from the experimental results at each level, and σ_2^2 was calculated from the experiment results at all six levels of each factor. After the single-factor tests, an orthogonal test was conducted to find the suitable combination of the three factors. The single-factor and orthogonal test analyses were conducted in Microsoft Excel. The assumptions and statistical analyses of the single-factor and orthogonal tests were described in detail by Montgomery (2001).

Table 1. Factors and levels in single-factor tests.[a]

Factor	Levels
h (mm)	130, 160, 190, 220, 250, 280
H (mm)	40, 60, 80, 100, 120, 140
t (s)	2, 4, 6, 8, 10, 12

[a] h = distance from microphone A to port opening, H = height of loudspeaker above port opening, and t = testing time.

Actual Volume Measurement of Watermelon

The actual volume of the watermelon was determined by water immersion. As the traditional water immersion method, also called the displacement method, is inconvenient, we made an improvement, as shown in figure 3. In a barrel, we first determined the water level height h' that corresponded to volume V_0, which was larger than the volume of a watermelon. We then placed a watermelon in the empty barrel, held it at the bottom with a sinker rod, and added volume V_1 of water to the barrel using a 2 L graduated cylinder with a scale resolution of 20 mL until the water level reached height h'. Thus $V_0 - V_1$ was the actual volume of the watermelon.

The volume of the internal hollow of the watermelon was measured after the watermelon was cut for observation by pouring water into the cavity so that water infiltrated into the large cavity as well as the small holes. The volume of the internal hollow was calculated by subtracting the volume of the remaining water in the graduated cylinder from the filled volume of the graduated cylinder.

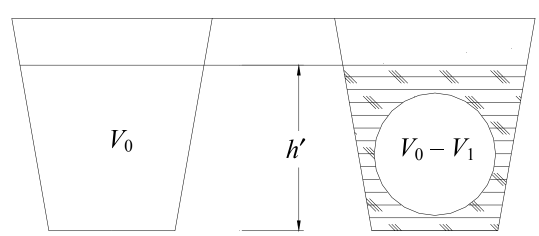


Figure 3. Schematic of improved water immersion method.

Data Analysis

After determining the Helmholtz resonant frequency and actual volume of the watermelons, each watermelon was cut to observe its degree of internal hollow and the state of the flesh. The 176 watermelons were then separated into two sets: 119 were used as the calibration set, and 57 were used as the validation set. The calibration set had 73 normal and 46 hollow watermelons. The validation set had 35 normal and 22 hollow watermelons.

Using the density as the input variable and comparing with the categorical variable of normal and hollow watermelon (given a dummy value of 0 and 1, respectively), binary logistic and SVM methods were used to perform classification. In the binary logistic method, the dependent variable is always dichotomous. Unlike linear regression, the goal of its regression is to assess the likelihood of falling into one of the outcome categories based on a set of predictors (Maroof, 2012). SVM was first proposed by Cortes and Vapnik (1995). Given a set of training examples, each is marked as belonging to one of two categories, and then an SVM training algorithm builds a model that assigns new examples into one category or the other. The binary logistic and SVM methods were carried out with SPSS 20.0 (IBM SPSS, Inc., Chicago, Ill.) and Matlab 7.11 (MathWorks, Inc., Natick, Mass.), respectively.

Results and Discussion

Density Distribution

The distribution of the densities of the 176 sample watermelons is shown in figure 4, which also identifies normal watermelons, watermelons with internal hollows or porous tissue, and watermelons with water and internal hollows. As shown in figure 4, the density of immature watermelons was sometimes greater than 1.05 g cm^{-3}, and neither hollows nor porous tissue were found in such high-density watermelons. In the density range of 0.925 to 1.025 g cm^{-3}, most of the watermelons had no hollows, and only small holes around the seeds were found in a few watermelons. However, there were several hollow watermelons that perhaps were over-ripe so that their flesh had deteriorated as water; thus, their density was greater than 0.925 g cm^{-3}. In the density range of 0.877 to 0.925 g cm^{-3} (box in fig. 4), there was no apparent boundary for classifying hollow and normal watermelons. In hollow watermelons, only narrow cracks and small holes around seeds were found, which was similar to the findings of a previous study (Kato, 1997). Watermelons with densities less than 0.877 g cm^{-3} had obvious cavities or porous tissue. An analysis of variance (ANOVA) for density and quality class (normal and hollow watermelons) showed that there were differences between the densities of normal and hollow watermelons.

Figure 5 shows that the degree of internal hollow increased as the watermelon density decreased. Among the 68 hollow watermelons, we determined only 55 volume values for the internal hollows because some internal hollows were too small and some watermelons were over-ripe. Figure 6 shows that there was a negative correlation between the internal hollow volume and the density of hollow watermelons, except for three hollow watermelons with densities less than 0.750 g cm^{-3}. The lower the density, the larger the hollow was.

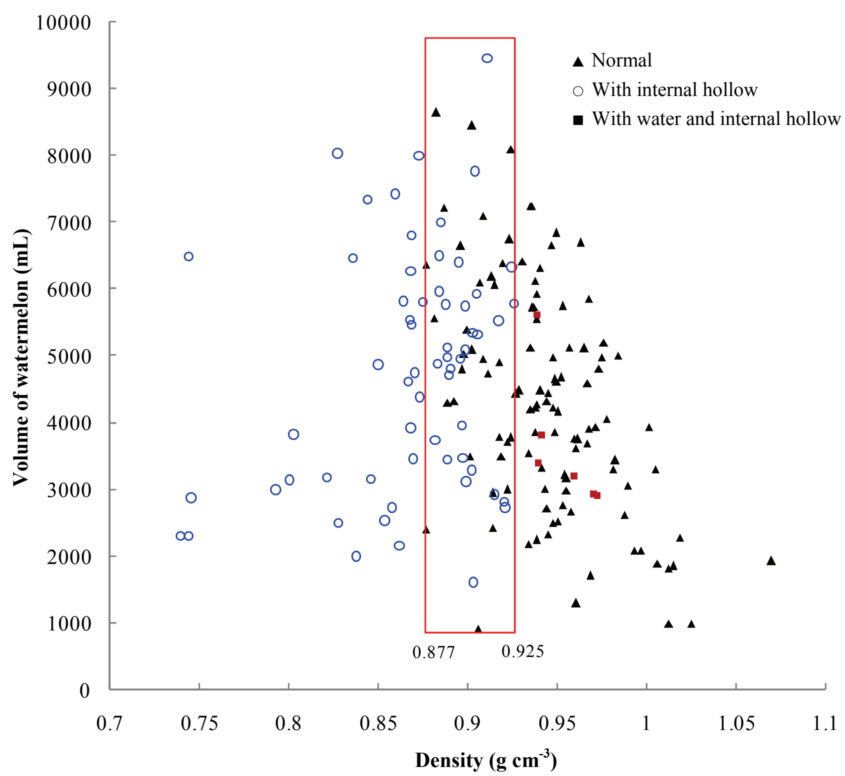
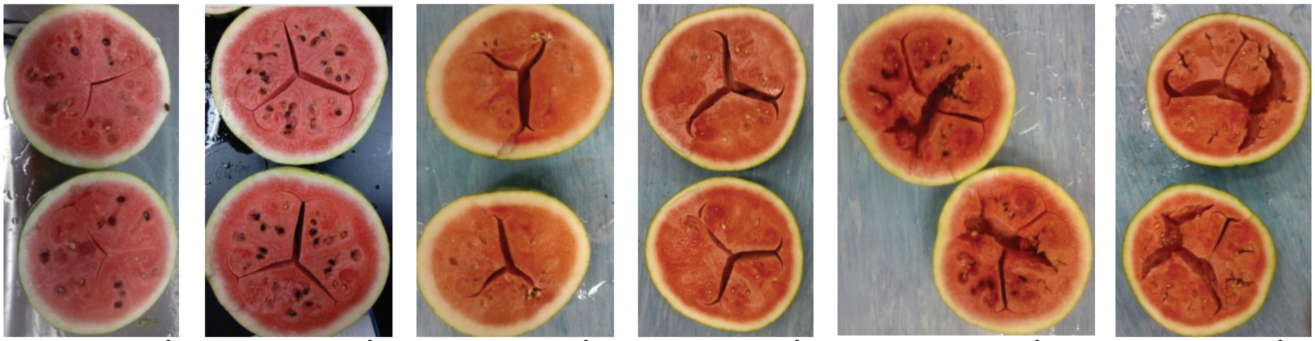


Figure 4. Density distribution of 176 watermelons.



ρ = 0.9211 g cm^{-3} ρ = 0.8988 g cm^{-3} ρ = 0.8698 g cm^{-3} ρ = 0.8363 g cm^{-3} ρ = 0.8032 g cm^{-3} ρ = 0.7446 g cm^{-3}

Figure 5. Watermelon densities with different degrees of hollow heart.

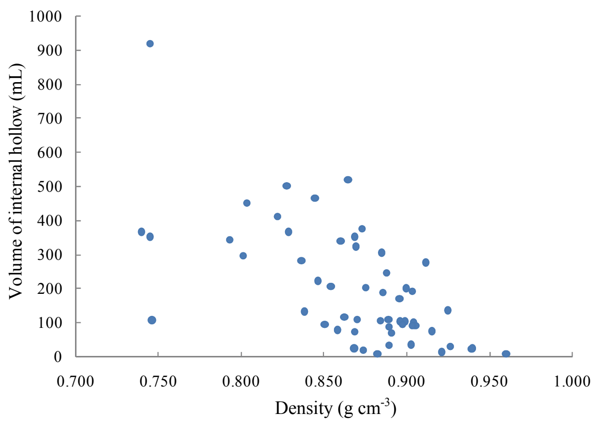


Figure 6. Scatter diagram of the internal hollow volume and the density of hollow watermelons.

Suitable Parameters of Helmholtz Resonant Detection System

From the single-factor experiment results (table 2), it was found that h did not seem to have a significant influence on the Helmholtz resonant frequency due to its small σ_2^2 value (0.0529). The σ_2^2 values for H and t were much greater than for h and were both larger than 0.1. According to the smaller σ_1^2 values for each level of the three factors and considering the measurement efficiency (i.e., the testing time should be no longer than 10 s), the 220, 250, and 280 mm levels for factor h, the 80, 100, and 120 mm levels for factor H, and the 6, 8, and 10 s levels for factor t were chosen for the orthogonal test to find the optimal factor and level combination, as shown in table 3.

Table 2. Single-factor experiment results.

Factor	Level	σ_1^2	σ_2^2
h (mm)	130	0.0781	0.0529
	160	0.0260	
	190	0.0684	
	220	0.0553	
	250	0.0260	
	280	0.0553	
H (mm)	40	0.1562	0.1025
	60	0.0553	
	80	0.0944	
	100	0.1335	
	120	0.0553	
	140	0.1465	
t (s)	2	0.2734	0.1182
	4	0.1562	
	6	0.1041	
	8	0.0944	
	10	0.0293	
	12	0.0553	

Table 3. Factor levels used in orthogonal test.

Level	Factor A (h, mm)	Factor B (H, mm)	Factor C (t, s)
1	220	80	6
2	250	100	8
3	280	120	10

The results of the orthogonal test are presented in table 4. The evaluation index values (K, k, and R) were calculated and are also listed in table 4: K_1, K_2, and K_3 are the amounts of the frequency values at levels 1, 2, and 3; k_1, k_2, and k_3 are the means of K_1, K_2, and K_3, respectively; and R (range) is the difference between the maximum and minimum K values. As shown in table 4, according to the R values, it can be seen that the influence of the three factors on the Helmholtz resonant frequency decreased in the order B > C > A. The height (H) of the loudspeaker above the port opening was found to be the most important factor for determining the frequency due to its maximum R value, which is similar to the finding of Webster (2010) that the sound source is very important. The distance (h) from microphone A to the port opening was found not to be a significant influence for determining the resonant frequency, which corresponded to the

Table 4. Orthogonal test scheme and analysis of test results.

Test Number	Level: Factor A (h, mm)	Level: Factor B (H, mm)	Level: Factor C (t, s)	Frequency (Hz)
1	1	1	1	57.1875
2	1	2	2	57.5000
3	1	3	3	57.5000
4	2	1	2	57.1354
5	2	2	3	57.3438
6	2	3	1	57.4479
7	3	1	3	57.3958
8	3	2	1	57.1875
9	3	3	2	57.5000
K_1	172.1875[a]	171.7188	171.8229	
K_2	171.9271	172.0312	172.1354	
K_3	172.0833	172.4479	172.2396	
k_1	57.3958[b]	57.2396	57.2743	
k_2	57.3090	57.3438	57.3785	
k_3	57.3611	57.4826	57.4132	
R	0.0347[c]	0.2430	0.1389	
Influence	B > C > A			
Optimal levels	A = 1, B = 3, C = 3			

[a] $K_i^A = \Sigma$(amount of frequency values at level i of factor A).
[b] $k_i^A = k_i^A / 3$.
[c] $R^A = \max\{K^A\} - \min\{K^A\}$.

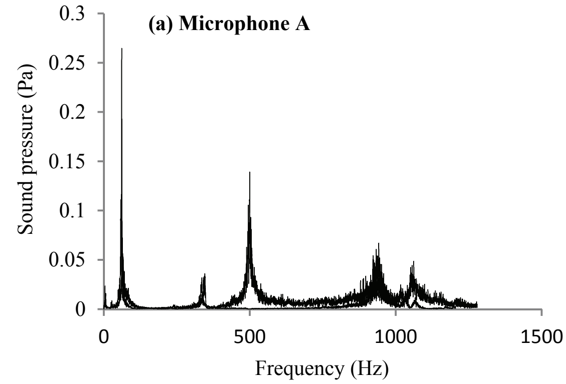
single-factor test results. According to the maximum values of *K* or *k*, the optimal parameter levels were 220 mm for the distance from microphone A to the port opening, 120 mm for the height of the loudspeaker above the port opening, and 10 s for the testing time.

Watermelon Volume Detection

Frequency spectrum plots for each microphone are shown in figure 7. Figure 7a is the sound signal recorded with microphone A after FFT, which shows the Helmholtz resonance caused by the resonator. Figure 7b is the sound signal recorded with microphone B after FFT, which shows the source signal from the loudspeaker. As shown in figure 7, there was a significant difference between the sound signals obtained with each microphone, which implies that the Helmholtz resonant frequency was obviously different from the driving frequency. In addition, the resonant frequency was prominent among the other peaks in the spectrum, corresponding to the finding of Nishizu et al. (2001).

Figure 8 shows a typical resonant frequency comparison for three different-size watermelons. As shown in figure 8, the resonant frequency increased with increasing watermelon volume, which corresponds to equation 3, i.e., the resonant frequency increased as the object's volume increased in the chamber. This occurred because the effective volume in the chamber decreased as the object's volume increased, and the sound vibration in a much smaller space led to a more significant response.

Figure 9 shows a plot of actual volume and frequency for the 119 watermelons in the calibration set. The relationship tended to be linear and quadratic; however, equation 4 shows that volume and frequency should have a negative quadratic relationship. Therefore, we performed regressions of volume and frequency using three models (linear, quadratic, and negative quadratic) in SPSS. The results are shown in table 5. Each model resulted in a high R^2 value (0.971, 0.977, 0.976, respectively), which indicates that volume and frequency have a strong relationship. However, the standard error of the estimate (SEE) was relative higher than in previous studies on small-size fruits using other methods (Moreda, 2004; Jarimopas et al., 2005), which indicates that the prediction accuracy needs to be improved. This error could come from the actual volume measurement



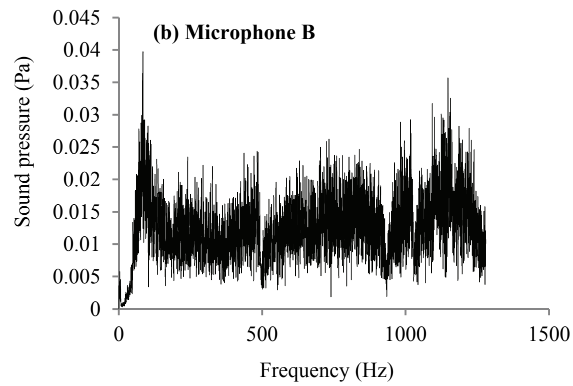


Figure 7. Frequency spectrum plots for microphones A and B.

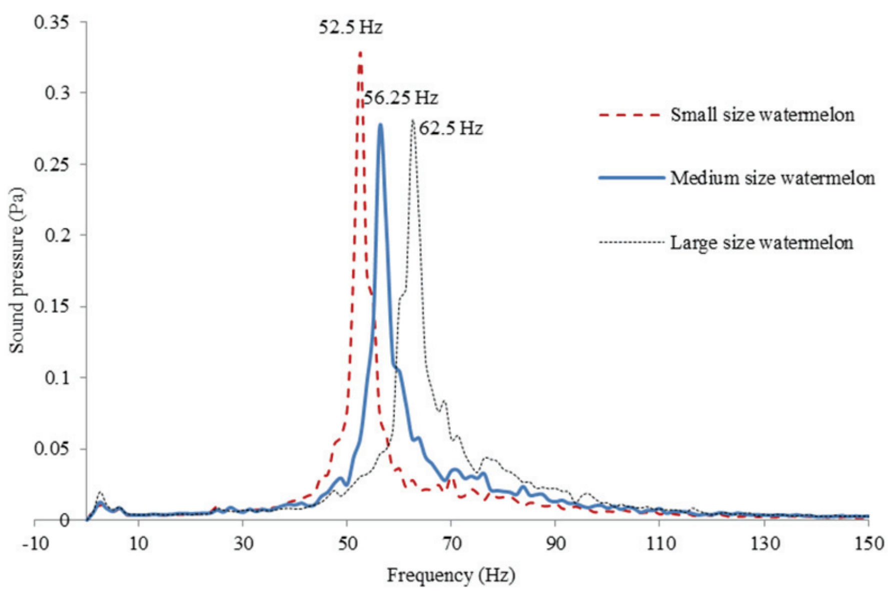


Figure 8. Frequency spectrum plots for three watermelon sizes.

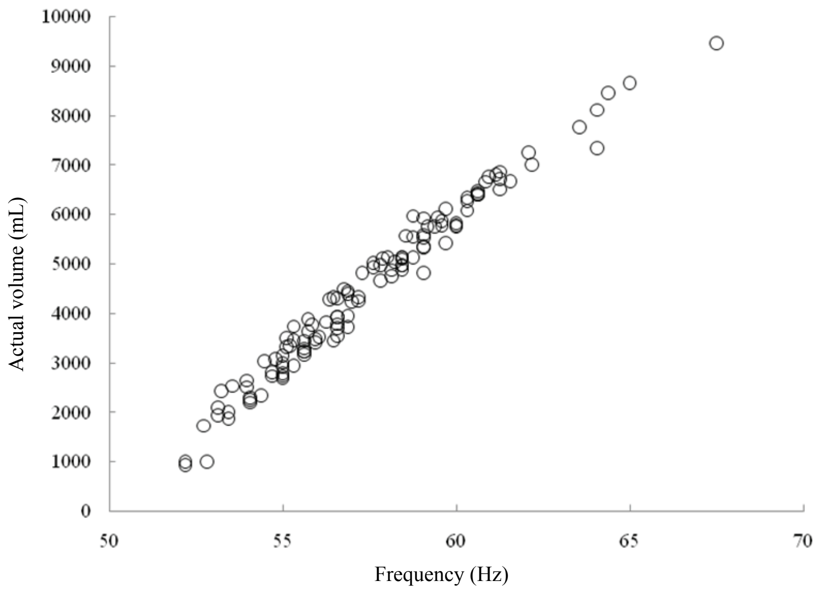


Figure 9. Scatter diagram of actual volume and frequency for 119 watermelons.

Table 5. Regression results of three models (SEE = standard error of estimate; NA = SPSS could not calculate the parameter).

Regression Model	R	R^2	Adjusted R^2	SEE (%)	F	Sig.	Regression Equation
Linear	0.985	0.971	0.971	6.783	3944.896	0.000	$y = 575.744 - 28603.327x$
Quadratic	0.988	0.977	0.977	6.100	2457.489	0.000	$y = -65158.960 + 1831.112x - 10.748x^2$
Negative quadratic	0.988	0.976	NA	5.232	NA	NA	$y = 21672.981 - 56344468.31x^{-2}$

Table 6. Classification results of watermelons for binary logistic and SVM methods.

Model Used to Calculate Volume	Binary Logistic Method: Actual Category	Predicted Category 0	Predicted Category 1	Correct Percentage (%)	Overall Correct (%)	SVM Method: Actual Category	Predicted Category 0	Predicted Category 1	Correct Percentage (%)	Overall Correct (%)
Original (water immersion)	0	33	2	94.3	91.2	0	33	2	94.3	91.2
	1	3	19	86.4		1	3	19	86.4	
Theoretical (eq. 4)	0	30	5	85.7	80.7	0	34	1	97.1	66.7
	1	6	16	72.7		1	18	4	18.2	
Linear	0	30	5	85.7	78.9	0	25	10	71.4	75.4
	1	7	15	68.2		1	4	18	81.8	
Quadratic	0	29	6	82.9	78.9	0	24	11	68.6	77.2
	1	6	16	72.7		1	2	20	90.9	
Negative quadratic	0	30	5	85.7	82.5	0	23	12	65.7	75.4
	1	5	17	77.3		1	2	20	90.9	

method as well as from environmental sound and temperature drift effects.

CLASSIFICATION OF WATERMELONS

Using the three regression models, we calculated the volumes of the 57 watermelons in the validation set. We also calculated their volumes using equation 4 (theoretical model) and water immersion (original model). Dividing mass by volume, the densities of the watermelons were obtained. Using density as the input variable, and comparing with the categorical variable for normal and hollow watermelons (0 and 1, resspectively), the binary logistic and SVM methods were used to classify the watermelons. Table 6 shows that the original model showed good classification of both normal and hollow watermelons with each prediction method. The overall percentage was 91.2% for both methods, which corresponds to the results shown in figures 5 and 6. The correct classification results for the other four models (theoretical, linear, quadratic, and negative quadratic) with the binary logistic method were 80.7%, 78.9%, 78.9%, and 82.5%, respectively. With the SVM method, the results were 66.7%, 75.4%, 77.2%, and 75.4%, respectively. The negative quadratic model showed better performance than the other three models, which corresponded to the Helmholtz resonance theory that volume and frequency have a negative quadratic relationship. As mentioned by Webster (2010), when a Helmholtz resonance system is designed, either empirical or improved Helmholtz equations should be used.

CONCLUSION

Helmholtz resonance was investigated to establish an effective method for measuring watermelon volume to predict internal hollows. The negative quadratic model gave more precise prediction results for frequency and volume, which corresponded to Helmholtz resonance theory. The binary logistic method based on the density obtained by the negative quadratic model showed better performance in predicting hollow watermelons, obtaining a correct percentage of 82.5%.

Further work will be aimed at designing a new method for actual volume measurement to improve the precision of the prediction results. Temperature compensation, environmental sound level, and the influence of sample position should also be taken into consideration.

Acknowledgements

The authors gratefully acknowledge the financial support provided by the National 863 Project of China (Grant No. 2012AA10A504).

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