WATERMELON MATURITY DETERMINATION IN THE FIELD USING ACOUSTIC IMPULSE IMPEDANCE TECHNIQUES

M. L. Stone, P. R. Armstrong, X. Zhang, G. H. Brusewitz, D. D. Chen

ABSTRACT. *A portable system using acoustic impulse impedance techniques was developed to nondestructively determine watermelon maturity. The system was used in the field to measure the maturity of three watermelon varieties 'Allsweet', 'Sangria' and 'King of Hearts'. Frequency domain parameters from the impulse response were compared with sugar content, flesh color, Effe-gi firmness and mass for individual melons. The effect of testing the melons in their natural growing position and resting on a hard base was determined. The system was also examined as a method to detect hollow heart in watermelons. Correlations between acoustic and destructive maturity parameters indicated relationships were too weak to be of value for maturity sorting. Relationships between acoustic parameters and level of hollow heart were weak for 'King of Hearts' but much stronger for the 'Black Diamond' cultivar.* ***Keywords.*** *Nondestructive, Ripeness.*

Watermelon is traditionally a popular summer fruit with abundant domestic supply occurring from May through September. The eating quality of this fruit depends largely on picking mature melons with adequate ripeness development. Quality may or may not improve with storage. Generally, optimum eating quality requires adequate sugar and flavor development and a center meat with a melting texture that progresses to a crisp texture towards the rind. Good red color development is also desirable but varies by variety. Immature or under-ripe melons have less internal color development, less sugar and flavor development, and have a firmer texture than those at optimum ripeness. As watermelons progress from ripe to over-ripe, flavor and texture degrade dramatically. It is very difficult to judge ripeness by outward characteristics such as size, external color, stem condition or feel. General recommendations given to produce managers are that good, ripe melons should be firm, symmetrical and fresh looking with an attractive waxy bloom (Produce Availability and Merchandising Guide, 1995). Determining optimum watermelon maturity at harvest time is thus a critical but difficult task, even for experienced growers.

A traditional practice is to thump or slap the melon and judge ripeness and defects based on the sound. Material properties of the melon, which change with ripeness, will affect the emitted sound. A hollow, low-pitched sound generally indicates a ripe melon. While this may be an adequate method for persons with considerable experience, this does not work for an inexperienced ear. Thus, an objective, nondestructive technique is needed to field test melons for ripeness. Use of such a technique during picking would help to assure consistent quality is being delivered to marketers, retailers, and consumers.

LITERATURE REVIEW

Frequency response techniques have been studied as a method for non-destructive fruit and vegetable texture measurement for many years. Fundamentally, a fruit or vegetable exhibits resonant frequencies which are dependent on shape and material properties. Techniques which have been employed to excite vibrations, support the specimen and sense the response have differed among researchers. Spectrum analysis is predominantly used to characterize vibrational behavior. Peleg et al. (1989) measured the transmitted energy through avocado fruit by mechanically coupling the fruit to a vibrational source. Firmness indices based on that test were found to be sensitive to changes in fruit maturity. Abbott et al. (1968) applied sonic vibrations to a whole apple to excite resonance at different frequencies. They found that the resonant peak of the second-lowest frequency observed, was associated with flexural vibrations and strongly influenced by apple mass and firmness. Based on that observation, they derived a stiffness coefficient (f^2m, f = resonant frequency, m = mass) which was highly correlated with fruit firmness. Finney (1970, 1971) further studied the sonic vibration technique for evaluating firmness of intact apples and peaches. Cooke (1970) used a theoretical analysis of a vibrating elastic sphere to indicate that the shear modulus of fruit flesh was proportional to $f^2m^{2/3}$. This was similar to the stiffness coefficient but indicated a smaller contribution by the mass.

The two indices, f^2m and $f^2m^{2/3}$, have been widely used by other authors for firmness measurement of fruits

---

Article was submitted for publication in February 1996; reviewed and approved for publication by the Information and Electrical Technologies Div. of ASAE in August 1996. Presented as ASAE Paper No. 94-6024.

Approved for publication by the Director, Oklahoma Experiment Station, Stillwater.

The authors are **Marvin L. Stone**, ***ASAE Member Engineer,*** Associate Professor, **Paul R. Armstrong**, ***ASAE Member Engineer,*** Assistant Researcher, **Xihai Zhang**, Graduate Assistant, **Gerald H. Brusewitz**, ***ASAE Fellow Engineer,*** Regents Professor, **Ding D. Chen**, Graduate Assistant, Biosystems and Agricultural Engineering Dept.,Oklahoma State University, Stillwater, Okla. **Corresponding author:** Paul R. Armstrong, Oklahoma State University, Biosystems and Agric. Engineering Dept., Rm. 214C Ag Hall, Stillwater, OK 74078-6021; telephone: (405) 744-5289; fax: (405) 744-6059; e-mail: <parmstr@agen.okstate.edu>.

VOL. 39(6):2325-2330

and vegetables. Hardenburg et al. (1977) used f^2m as a firmness index in sonic vibration tests of apples. Magness-Taylor (MT) firmness was related to the firmness index with a linear correlation coefficient of 0.76. They noted that the sonic firmness index may be more sensitive than the penetrometer test to changes in apples ripeness. Armstrong et al. (1989) used an impulse to excite resonance in an apple. A particular resonant frequency mode was used in an elastic sphere model to predict elasticity of the apple tissue. Good correlation between predicted and measured core modulus of elasticity was observed while the correlation was poor between predicted elasticity and MT firmness. Abbott et al. (1992) concluded that sonic resonance functions correlated significantly with the mean of inspector's sensory scores and with MT firmness for stored apples. Sonic measurement was considered to represent the firmness of the entire fruit, while MT firmness was site dependent. Applying acoustic impulse response techniques, Vervaeke et al. (1993) developed a critical stiffness factor ($f^2m^{2/3}$) to determine the allowable shelf life of apples under different storage conditions. Verstreken et al. (1993) monitored peach maturity development using the stiffness factor ($f^2m^{2/3}$) as a firmness indicator.

Limited information is available for application of acoustical impulse techniques to watermelon maturity measurement. Clark (1975) measured the time required for a sound wave transmitted through or reflected from the melon to decay. The results were well correlated to the color of the melon meat. As the meat matured (increased red color), the decay time increased. The correlation between decay time and MT firmness was poor. By measuring acoustic properties of apples and watermelons, Yamamoto et al. (1980) found that firmness indices (f^2m, $f^2m^{2/3}\rho^{1/3}$) were highly correlated with the MT firmness for apples, but had poor correlation with the flesh firmness for watermelons (ρ = density).

Farabee and Stone (1991) developed an acoustical impulse response system to determine watermelon maturity. The hand-held sensor contained both the impulse generator and the vibration signal receiver. Two frequency domain parameters, center frequency of the narrowest 50% energy band and energy content of the frequency band from 85 to 160 Hz were evaluated. The correlation coefficients of these two parameters with sugar content were 0.67 and 0.56, respectively. When firmness data were added to the multiple regression model, the correlation coefficients increased to 0.73 and 0.63, respectively. The same system was used by Chen (1993) to estimate peach maturity of five cultivars. Good correlation was found between impulse response parameters and Effe-gi firmness.

The objectives of this study were to use the acoustic impulse impedance instrument previously developed by Farabee and Stone (1991) to: (1) test the device for determination of ripeness and the physical defect, hollow heart; (2) test for differences between sampling location, order of sampling and the type of supporting base; and (3) determine the correlations between acoustic impulse parameters and measured ripeness indicators for watermelon.

Materials and Methods

This study was designed to evaluate acoustic impulse parameters as indicators of watermelon ripeness and condition. The study focused on determining relationships between nondestructive impulse parameters and traditional destructive indicators of ripeness. All testing was done at the Oklahoma Vegetable Research Station near Bixby, Oklahoma. Watermelon varieties tested for ripeness were 'Allsweet', a long-shaped variety with full seed development, 'King of Hearts', a round to oval seedless variety, and 'Sangria', a variety similar to 'Allsweet' but typically not as long. 'Black Diamond', an older, large and long variety with irregular cross-sectional shape, was used for hollow heart studies as were 'King of Hearts' melons.

The sensor and recording system used to acquire the acoustic impulse information is depicted in block-diagram form in figure 1. The acoustic impulse probe is described by Farabee and Stone (1991). The probe is a closed-end, plexiglass cylinder approximately 5 cm in diameter and 15 cm long. A thin, disk-shaped, ceramic piezoelectric element, bonded to a similar sized thin brass disk, is mounted at the end of the cylinder and held in contact with a melon. A solenoid, inside the cylinder, is used to deliver a mechanical impulse to the flat face of the piezo ceramic. The impulse is transferred through the ceramic to the watermelon. The resulting vibration of the melon due to the impulse, is sensed by the piezo element. The signal from the element was amplified and filtered through a fourth order low-pass active filter before digitization by the data acquisition unit. Anti-aliasing and noise removal is accomplished with the filter. A battery powered data acquisition unit (I/O Tech model 100, Cleveland, Ohio) was used for data sampling. The acoustic signal sampling frequency was 5000 Hz with 12 bit precision. An Intel 486 based laptop PC was used to process data and control the operation of the data acquisition unit. The laptop could acquire the impulse data, compute the Fast Fourier transform (1024 pts), and store and display all relevant information in < 1 s. The hand control shown in figure 1 consisted of a simple push button mounted in a conveniently sized cylinder. The contact closure was sensed with the data acquisition system and used to initiate the mechanical impulse and sampling sequence. The entire battery operated system was mounted on a backpack frame for portability. Destructive analyses were performed to estimate ripeness after acoustic impulse information was

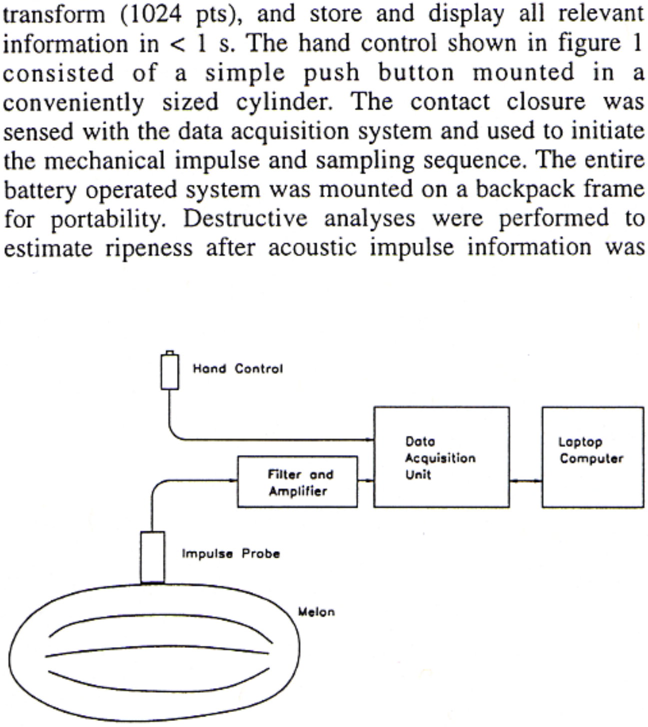

Figure 1–Acoustic impulse apparatus.

Table 1. Parameters measured in the destructive analysis

Parameter	Unit of Measurement	Instrument and Model Number
Tissue Color	a* value from L*,a*,b*	Minolta Model CR-300 chroma meter
Effe-gi firmness	kg	McCormick Model FT-011 fruit pressure tester
Mass	kg	Ohaus Model DS5-M, 0-20 Kg scale
Soluble solids	% Brix	Fisher Scientific 0-32% hand-held optical refractometer

gathered. The destructive parameters measured, and the instrumentation used, are described in table 1.

Acoustic impulse parameters were collected while the melons were in the field, in their natural growing position, with stems attached. Measurements of acoustic parameters were taken at three different locations on the melon. The melons were rotated in-place to gain access to alternate locations. The locations were selected within the center third of the melon, between the stem and blossom end. The initial location was selected opposite the ground spot. Two additional locations were selected away from the first location while avoiding the ground spot. The sensor head was always held at the top of the melon for measurement. Melons were then cut from the stem and placed on a hard base, a 2 cm × 25 cm × 50 cm wooden plank, where tests were repeated at the same measurement locations.

Each melon was weighed and then sectioned into halves with the cut running through the blossom and stem end. Color (a*), firmness, and soluble solids were measured at four positions, approximately 5 cm from the outer rind of the melon.

EVALUATION OF ACOUSTIC PARAMETERS

Figure 2 depicts a typical time domain impulse response digitally recorded by the computer. The Fast Fourier transform of the data was normalized using the frequency with the largest amplitude (fig. 3). Eight acoustic parameters were evaluated to characterize the spectrum profile. Those parameters were BM85-160, BM40-90, BM60-110, BM70-120, BM80-130, BM100-180, BM120-200, and CFN50. BM signifies band magnitude, the two numbers are the starting and ending frequencies of that band. For example, BM85-160 was calculated by summing the normalized spectrum magnitudes from 85 to 160 Hz and dividing that sum by the sum of spectrum magnitudes between 0 and 500 Hz. This value is proportional to the energy content between these frequencies. The energy content beyond 500 Hz was insignificant and therefore ignored. CFN50 was the center frequency of the narrowest 50% energy band. It was calculated by searching through the spectrum to find the narrowest frequency band that contained 50% of the total energy of the spectrum. Other research has indicated correlation of impulse parameters with destructive measurements is fruit dependent and cultivar dependent. Farabee and Stone (1991) determined that BM85-160 and CFN50 had the highest correlation with destructively measured parameters for watermelon while Zhang et al. (1994) found that BM80-130 was a better parameter for peaches. Multiple parameters were evaluated in this research to characterize the spectrum profile while the different supports and measurement locations were examined for their effect on impulse parameters.

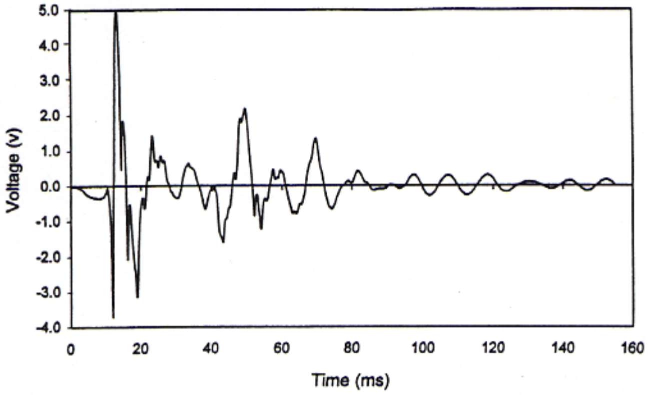

Figure 2–A typical time domain impulse response signal.

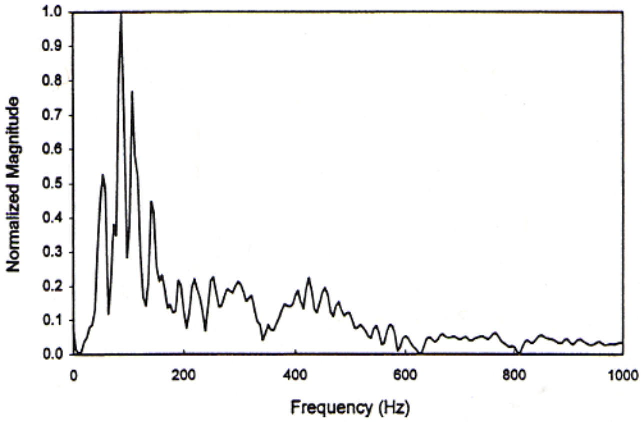

Figure 3–A typical frequency domain impulse response signal.

RESULTS

TEST FOR RIPENESS

Analysis of variance was performed to determine if differences existed between supporting bases (soil vs. hard board), impulse location on the melon and the order of the impulse. The results showed no significant difference existed (5% level) between impulse test locations for each support base. Acoustic measurements were significantly different though between the supporting bases at the 1% level for 'King of Hearts' and at the 5% level for 'Allsweet'. Differences were not significant for 'Sangria' melons. Because there was no difference between measurement location, the three measurements of each acoustic parameter for each watermelon were averaged for subsequent analysis. Data were analyzed separately for each type of base. Each watermelon cultivar responded differently to the measured ripeness indicators and will be discussed separately.

'Allsweet'. A linear regression model was used to correlate each acoustic parameter with destructively measured ripeness indicators. An analysis was performed separately for the soil and hard supporting bases (table 2). For watermelons tested at their natural location on the ground, the best correlations between an acoustic parameter and each destructive parameter were, 0.636

Table 2. Absolute value of correlation coefficients between acoustic parameters and other ripeness indicators of 'Allsweet' watermelon for two support bases, (n = 29)

	Soil Base				Hard Base			
	Sugar Content	Tissue Color	Mass	Effe-gi Firmness	Sugar Content	Tissue Color	Mass	Effe-gi Firmness
BM85-160	0.186	0.076	0.414	0.231	0.155	0.125	0.217	0.187
BM40-90	0.636	0.563	0.516	0.394	0.543	0.494	0.584	0.138
BM60-110	0.503	0.479	0.351	0.344	0.408	0.395	0.488	0.127
BM70-120	0.363	0.398	0.169	0.225	0.264	0.284	0.382	0.057
BM80-130	0.167	0.245	0.006	0.098	0.108	0.136	0.235	0.011
BM100-180	0.534	0.344	0.652	0.428	0.403	0.285	0.576	0.216
BM120-200	0.586	0.501	0.676	0.529	0.343	0.368	0.682	0.183
CFN50	0.362	0.396	0.208	0.194	0.387	0.399	0.462	0.094
Tissue color	0.898				*			
Mass	0.492	0.451			*	*		
Effe-gi	0.671	0.694	0.418		*	*	*	

* Same as soil base.

(BM40-90 and Sugar Content), 0.563 (BM40-90 and Tissue Color), 0.676 (BM120-200 and Mass) and 0.529 (BM120-200 and Effe-gi Firmness). The same parameters had the best correlations for the hard base except for BM120-200 and Effe-gi Firmness where low correlations were observed for all acoustic parameters.

For correlations between destructive parameters only, tissue color and sugar content was the highest (r = 0.898). The relationship between these two parameters was considerably better than either of their relationships with the BM40-90 acoustic parameter. The second and third best correlations were between Effe-gi firmness and sugar content and Effe-gi firmness and tissue color.

A stepwise multiple regression procedure was used to include more than one destructively measured ripeness indicator in a linear model. The model developed for soil base measurements using the parameters BM40-90, sugar content and mass was:

$$\mathrm{BM40\text{-}90} = 0.6356 - 0.0277S - 0.0063M$$

$$r = 0.678 \qquad (1)$$

The model developed for hard base measurements using the parameters BM40-90, sugar content, Effe-gi firmness and mass was:

$$\mathrm{BM40\text{-}90} = 0.9241 - 0.0349S - 0.0152E - 0.0111M$$

$$r = 0.746 \qquad (2)$$

Where S is sugar content, M is mass in kg, and E is Effe-gi firmness in N. Adding more destructive terms increased the correlation in all models by 6-16%.

Table 3. Absolute value of correlation coefficients between acoustic parameters and other ripeness indicators of 'King of Hearts' watermelon for two support bases, (n = 60)

	Soil Base				Hard Base			
	Sugar Content	Tissue Color	Mass	Effe-gi Firmness	Sugar Content	Tissue Color	Mass	Effe-gi Firmness
BM85-160	0.069	0.101	0.382	0.381	0.035	0.134	0.183	0.201
BM40-90	0.244	0.348	0.342	0.397	0.236	0.483	0.014	0.315
BM60-110	0.168	0.350	0.068	0.154	0.160	0.372	0.080	0.028
BM70-120	0.039	0.158	0.077	0.046	0.013	0.266	0.188	0.057
BM80-130	0.203	0.236	0.112	0.335	0.140	0.257	0.167	0.163
BM100-180	0.082	0.142	0.295	0.248	0.223	0.106	0.129	0.048
BM120-200	0.219	0.075	0.022	0.334	0.038	0.015	0.092	0.292
CFN50	0.092	0.165	0.093	0.260	0.112	0.351	0.204	0.273
Tissue color	0.657				*			
Mass	0.115	0.347			*	*		
Effe-gi	0.474	0.217	0.314		*	*	*	

* Same as for soil base.

'King of Hearts'. The acoustic parameters for 'King of Hearts' watermelons had poor correlation with all destructively measured ripeness parameters for both supporting bases (table 3). As such, none of the acoustic parameters could give an indication of destructive parameters. Destructively measured ripeness parameters generally had low correlation between themselves with the highest correlation coefficient occurring between tissue color and sugar content (r = 0.657). The best multiple regression model involved the BM40-90 parameter with a combination of watermelon mass, M, and tissue color, C, for the soil base:

$$\mathrm{BM40\text{-}90} = 0.2838 + 0.0144M - 0.0072C$$

$$r = 0.603 \qquad (3)$$

The following linear equation was found to be the best for the hard base measurements:

$$\mathrm{BM40\text{-}90} = 0.4007 - 0.0073C$$

$$r = 0.483 \qquad (4)$$

Adding other ripeness indicators to the model did not improve the correlation coefficient.

'Sangria'. Correlation coefficients between acoustic parameters and destructively measured ripeness indicators for 'Sangria' are shown in table 4. The best correlations were between CFN50 and tissue color (r = 0.664) for the soil base and BM60-110 and mass (r = 0.617) for the hard base. These values dropped considerably though when bases were switched (r = 0.372 and 0.352, respectively). All correlation values between acoustic parameters and sugar content, mass and Effe-gi firmness were very low. For the hard base, all were low except for mass. The correlations between destructively measured ripeness indicators were also very low.

The best multiple regression model between acoustic and destructive parameters obtained for the soil base was:

$$\mathrm{BM40\text{-}90} = 0.3105 - 0.0133C + 0.0102E$$

$$r = 0.733 \qquad (5)$$

For the hard base, a combination of sugar content and tissue color resulted in the best model:

$$\mathrm{BM40\text{-}90} = 0.1448 + 0.0141S - 0.0074C$$

Table 4. Absolute value of correlation coefficients between acoustic parameters and other ripeness indicators of 'Sangria' watermelon for two support bases, (n = 32)

	Soil Base				Hard Base			
	Sugar Content	Tissue Color	Mass	Effe-gi Firmness	Sugar Content	Tissue Color	Mass	Effe-gi Firmness
BM85-160	0.030	0.564	0.110	0.423	0.149	0.288	0.335	0.016
BM40-90	0.063	0.660	0.055	0.424	0.205	0.453	0.137	0.026
BM60-110	0.035	0.606	0.352	0.420	0.177	0.317	0.617	0.047
BM70-120	0.000	0.570	0.343	0.411	0.205	0.241	0.560	0.000
BM80-130	0.041	0.594	0.228	0.451	0.108	0.279	0.465	0.107
BM100-180	0.138	0.440	0.014	0.255	0.215	0.089	0.174	0.202
BM120-200	0.084	0.386	0.360	0.191	0.080	0.147	0.514	0.176
CFN50	0.058	0.664	0.168	0.359	0.260	0.372	0.033	0.027
Tissue color	0.181				*			
Mass	0.105	0.049			*	*		
Effe-gi	0.153	0.159	0.020		*	*	*	

* Same as for soil base.

$$r = 0.538 \qquad (6)$$

Tests for Hollow Heart

Hollow heart tests were performed in the laboratory for 'King of Hearts' melons on a hard base (n = 60). Hollow heart was subjectively classified by visual inspection into four index levels. Index level one had no hollow heart, level four had the worst condition of hollow heart. Acoustic parameters were correlated with parameters of sugar content, tissue color, mass, and hollow heart level. Similar to the field tests, the relationships between acoustic parameters were weak with the first three destructive parameters. Acoustic parameter correlation with hollow heart level was stronger. The best correlation for 'King of Heart' melons occurred with the acoustic parameter, BM60-110 and is the only result shown in table 5. Hollow heart tests were also completed on the variety 'Black Diamond' (n = 30). In this experiment fertilization was applied to induce hollow heart condition by providing an excess of nitrogen during the season. This procedure resulted in a fairly equal distribution of hollow heart development across index levels compared to 'King of Hearts' where only two melons were recorded at level three. Results from this test, also shown in table 5, show improved correlations. It is not evident if the improved correlation for 'Black Diamond' was due to a more uniform distribution of hollow heart across the index levels or if it is variety dependent. Several impulse parameters had good correlation with hollow heart for 'Black Diamond' melons.

Discussion and Conclusions

The correlation between destructively measured ripeness indices was predominantly poor. The exception was for 'Allsweet' watermelons which had good correlation between sugar content and color (r = 0.898) and to a lesser extent, between firmness and sugar content (r = 0.671) and tissue color (r = 0.694). The correlation coefficient between color and sugar content for 'King of Hearts' was 0.657; all others were poor. 'Sangria' melons had very poor correlations between all destructive measurements. These results indicate that relationships between destructive measurements are variety dependent and no single parameter is a good indication of ripeness for all watermelon varieties.

The best correlations between acoustic parameters and singular destructive parameters were generally too low to be reliable predictors to determine quality parameters. The 'Allsweet' acoustic parameter BM40-90 had the highest correlation with sugar content and color (0.494 to 0.636) and was reasonably consistent between support bases. Similarly, the BM120-200 parameter had the best correlation with mass (0.676 to 0.682). Correlations between destructive and acoustic parameters for 'King of Hearts' melons were all poor. For 'Sangria' melons, low correlations were observed and equivalent correlations between bases was not consistent. As an example the correlation between CNF50 and tissue color was 0.664 on the soil base but dropped to 0.372 on the hard base. For all varieties, correlations from multiple regression were as good or better than for single terms but were still too low for effective sorting. The differences in results observed between support bases is most likely attributed to the physical constraint placed on a melon when resting on the soil or on the hard base. The soil base formed to the surface of the melon and thus had a large contact surface while the hard base had a small contact surface. Resonant behavior would be altered depending on the physical support system.

Table 5. Absolute correlation coefficient between Melon Hollow Heart Index and selected Impulse Parameters for 'King of Heart ' and 'Black Diamond' melons

	BM 85-160	BM 60-110	BM 70-120	BM 80-130	BM 100-150
'King of Hearts'	*	0.584	*	*	*
'Black Diamond'	0.762	*	0.637	0.784	0.647

* Correlations less than 0.300 not shown.

The following conclusions were drawn from this study: The impulse acoustic impedance instrument was not a good predictor of sugar content, tissue color, mass or Effe-gi firmness for any variety. The better correlations found for one variety did not carry over to the other varieties and thus relationships seem to be variety dependent.

Correlations between destructive parameters for all melon cultivars indicated only tissue and sugar content were strongly related for 'Allsweet' (r = 0.898). Other relationships were weak to poor.

The measurement location on the watermelon as defined in the experimental procedures, did not have a significant effect on the sensor response whereas base support was significant for 'Allsweet' and 'King of Hearts' but not for 'Sangria' melons.

The best relationships between hollow heart condition and acoustic parameters yielded correlation coefficients of 0.584 (BM 80-130) and 0.784 (BM 60-110) for 'King of Hearts' and 'Black Diamond' watermelons, respectively. The latter results indicate that refinement of the acoustic method could lead to an acceptable level of sorting for hollow heart condition but may not work for all varieties.

References

Abbott, J. A., G. S. Bachmann, N. F. Childers, J. V. Fitzgerald and K. F. Matusik. 1968. Sonic techniques for measuring texture of fruits and vegetables. *Food Technology* 22(5):635-646.

Abbott, J. A., H. A. Affeldt and L. A. Liljedahl. 1992. Firmness measurement of stored 'delicious' apples by sensory methods, Magness-Taylor, and sonic transmission. *J. Amer. Soc. Hort. Sci.* 117(4):590-595.

Armstrong, P. R., H. R. Zapp and G. K. Brown. 1989. Impulsive excitation of acoustic vibrations in apples for firmness determination. ASAE/CSAE Paper No. 89-3052. St. Joseph, Mich.: ASAE.

Chen, D. 1993. Peach maturity estimation by sonic impulse testing. Unpubl. M.S. thesis. Stillwater, Okla.: Oklahoma State University.

Clark, R. L. 1975. An investigation of the acoustical properties of watermelon as related to maturity. ASAE Paper No. 75-6004. St. Joseph, Mich.: ASAE.

Cooke, J. R. 1970. A theoretical analysis of the resonance of intact apples. ASAE Paper No. 70-345. St. Joseph, Mich.: ASAE.

Farabee, L. M. and M. L. Stone. 1991. Determination of watermelon maturity with sonic impulse testing. ASAE Paper No. 91-3013. St. Joseph, Mich.: ASAE.

Finney, E. E. 1970. Mechanical resonance within Red Delicious apples and its relation to fruit texture. *Transactions of the ASAE* 13(2):177-180.

———. 1971. Random vibration techniques for nondestructive evaluation of peach firmness. *J. of Agric. Eng. Res.* 6(1):81-87.

Hardenburg, R. E., R. E. Anderson and E. E. Finney Jr. 1977. Quality and condition of 'Delicious' apples after storage at 0°C and display at warmer temperatures. *J. Amer. Soc. Hort. Sci.* 102(2):210-214.

Peleg, K., U. Ben-Hanan and S. Hinga. 1989. Classification of avocado by firmness and maturity. *J. of Texture Studies* 21(2):123-139.

Produce Merchandising and Availability Guide. 1995. Lenexa, Kans.: Vance Publishing Corp.

Verstreken, E., J. De Baerdemaeker and K. U. Leuven. 1993. Evolution of maturity of peaches during storage: Non-destructive stiffness measurement by acoustic impulse. ICPPAM Paper No. 93-1206. Bonn, Germany.

Vervaeke, F., H. Chen, J. De Baerdemaeker and J. U. Leuven. 1993. Applying the acoustic impulse response technique to determine the time for harvest and storage of the apple. ICPPAM Paper No. 93-1207. Bonn, Germany.

Yamamoto, H., M. Iwamoto and S. Haginuma. 1980. Acoustic impulse response method for measuring natural frequency of intact fruits and preliminary applications to internal quality evaluations of apples and watermelons. *J. of Texture Studies* 11(2):117-136.

Zhang, X., M. L. Stone, D. Chen, N. O. Maness and G. H. Brusewitz. 1994. Peach firmness determination by puncture resistance, drop impact, and sonic impulse. *Transactions of the ASAE* 37(2):495-500.