NONDESTRUCTIVE ACOUSTIC AND COMPRESSION MEASUREMENTS OF WATERMELON FOR INTERNAL DAMAGE DETECTION

P. R. Armstrong, M. L. Stone, G. H. Brusewitz

ABSTRACT. *Compression values of Slope, derived from the force-deformation curve, and force at 2.5 mm (0.1 in.) deflection (F@2.5) and the acoustic impulse response of watermelons were measured before and after successive drops from a height expected to cause internal damage. Spectral parameters were used as potential nondestructive predictors of internal damage while compression values were used as an estimate of internal damage. Results show that the mean Slope and F@2.5 parameters decreased significantly after the first drop. Subsequent drops resulted in significant but more gradual decreases in compression values. Multiple linear regression performed between spectral parameters and Slope, and spectral parameters and F@2.5 resulted in the same adjusted R^2 value of 0.70 for each. Following each drop, compression and acoustic regression values were highly variable and are likely affected by the structural differences between individual melons. Severely damaged melons were distinguishable with either acoustic or compression measurements, however, measurement variability would make sorting lesser-damaged melons difficult.*
Keywords. *Watermelon, Impact damage, Cracks.*

The U.S. per capita consumption of watermelon reached a peak of 7.3 kgs (16.1 lbs) in 1960, decreased to 4.8 kgs (10.7 lbs) in 1980, and then increased back to 6 kgs (13.3 lbs) by 1992 (Allred and Lucier, 1988). Part of this increase is attributed to the introduction of seedless melons which had a market share of 11% in 1988 and 33% by 1994, the largest increase of the 15 major fresh fruit ("The Packer's 1995 Fresh Trends").

Watermelons require extensive human handling during harvest and market distribution. Because of the weight and size of watermelon, it is difficult for workers to always use the proper care required during handling. Carelessness during packing and transit results in surface abrasion and damaging impacts to the melons. Severe impacts will cause obvious external damage but frequently internal damage, characterized by cracks in the pulp tissue, will be undetectable until the melon is cut open. Practices such as labor intensive packing into pallet cartons keep losses to less than 1% but shipping in non-containerized bulk results in losses of 11.3% (Allred and Lucier, 1988). While modest damage may not dramatically affect eating quality or shelf life, damage should be avoided or minimized. This is particularly true for melons destined for the precut market as cracks will diminish consumer appeal and create excessive waste. The ability to detect internal damage is highly desirable to maximize quality and deliverable quantity.

Research by Abbott et al. (1968), Clark (1975), and Yamamoto et al. (1980, 1981) proposed that resonant vibrations might be used to nondestructively determine physical properties or firmness of fruit. The purpose in seeking such a method was to replace the traditional destructive puncture test (Magness-Taylor, Effe-gi) with one that was nondestructive and an equally good indicator of maturity and eating quality. While much of the earlier research focused on apples, research with other produce was completed. Peleg et al. (1989) measured transmitted vibrational energy through avocado fruit and found relationships between energy and internal ripeness. Chen et al. (1996) used finite element modeling to study the resonant behavior of 'Galia' melons. He determined watercored fruit could be detected but not reliably because the change produced by this defect is subtle. Clark (1975) measured resonant decay times of watermelons and found good correlation with flesh or pulp color but not with firmness.

The appeal of an acoustic technique for determining watermelon maturity might be founded in the traditional method of slapping or tapping a melon to determine ripeness. Fundamentally, the spectral response of an undamaged or intact melon subjected to an impulse would be expected to change as either external or internal cracking occurs. Furthermore, as the integrity of the tissue diminishes due to the initiation or formation of cracks, the overall stiffness should decrease and consequently higher resonant frequencies of the melon would shift lower or diminish in relative amplitude. Based on this reasoning, the impulse response and compression tests of melons were compared before and after the melons were dropped from heights known to cause damage.

The objectives of this research were to determine if the response spectrum and compression values of watermelons change when internal damage was induced. Parameters

Article was submitted for publication in November 1996; reviewed and approved for publication by the Food & Process Engineering Inst. of ASAE in June 1997.

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

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

were also examined to determine if they could be used for sorting criteria to separate internally damaged melons from sound melons.

Materials and Methods

To investigate methods to detect internal damage, a procedure was required to artificially induce varying degrees of internal damage and then quantify this damage. Since no procedure was known to exist, it was decided that dropping a melon multiple times from a fixed height, not unreasonable in commercial handling, would be sufficient to cause a gradual increase of internal damage. The obvious disadvantages with this approach were that no absolute control of the quantity of damage could be achieved after each drop and a wide variability of damage would likely be sustained between individual melons.

To quantify damage, visual inspection was considered but requires cutting the melon open into multiple sections, without causing further damage, and ranking or measuring the quantity of internal breakage. Because of the complex ways in which internal breakage occurs in melons (circular cracks, line cracks, or crushing of the tissue) it was concluded that trying to measure or judge the extent of damage this way would introduce considerable measurement error. For this reason, it was decided that a compressive test on the whole melon would provide an estimation of internal damage. Alternatively, the number of times a melon was dropped could have been used but individual melons would likely respond differently to each drop.

Preliminary Tests

Preliminary tests were conducted to establish a drop height sufficient to cause internal damage without causing any apparent exterior breakage. Melons of the ‘Black Diamond’ cultivar were dropped onto a concrete floor from heights of 23, 25, 27.5, and 30 cm (9, 10, 11, and 12 in.). All melons were similar in size and were dropped on their side with the stem and blossom end horizontal. Results indicate a small difference in drop height greatly affects the external breakage susceptibility of melons (table 1). Melons dropped from 23 cm (9 in.) required from 11 drops to 60 drops before external breakage occurred; whereas, from 27.5 cm (11 in.) a maximum of only four drops were required to cause external damage. The additional energy generated during impact when dropping from 27.5 cm (11 in.) as opposed to 23 cm (9 in.) was easily sufficient to exceed strength limits of the rind and tissue and cause failure. External breakage lines occurred from either the stem to blossom end or directly across the midsection, perpendicular to the long axis. Internal damage was visually apparent as a loosening of the central section of the melon with fracturing occurring around the seed cavities. It was determined by visual inspection that a drop height of 25 cm (10 in.) was adequate to produce internal damage and that additional drops would increase internal damage without causing excessive external damage.

Table 1. The number of drops required to cause external breakage of ‘Black Diamond’ watermelon at different drop heights onto a concrete floor

Drop Height	23 cm (9 in.)	25 cm (10 in.)	27.5 cm (11 in.)	30 cm (12 in.)
Drops required before breakage	11-60	3-31	1-4	1-4
Number of melons tested	3	3	3	4

As no standard methodology existed for compressive testing, procedures were developed in preliminary tests. Undropped and multiple dropped melons were compressed to a fixed deflection in a universal testing machine to determine a deflection value that was repeatable and gave a clear indication between the different melon treatments but did not permanently damage the melon. Slope and maximum force, obtained from the force-deformation curve, were used to characterize compression. The procedure used is outlined below.

Nondestructive Compression and Acoustic Tests

Twenty-two ‘Crimson Sweet’ melons, which were judged to be mature, were picked on 9 August 1994 at the Oklahoma Vegetable Research Station near Bixby and tested the following day. Extreme care was taken in the picking and transportation of the melons to the test lab in Stillwater to avoid any damaging impacts. Melons were weighed and then dropped five times from a height of 25 cm (10 in.). Two compression and three acoustic measurements were taken prior to the first drop and after each successive drop. Dropping was achieved by placing the melons on an elevated horizontal platform and gently rolling them off onto the concrete surface. Each melon was oriented on the platform so that the same spot on the melon impacted the surface for each drop. Melons impacting the surface did not appear to have much rebound and were not disturbed until they were at rest. Three melons broke on the first, third and fourth drop before all drops were completed while the others remained intact with no visible external damage. External breakage was consistent with the preliminary test data for ‘Black Diamond’.

Compression tests for each melon were performed using a universal testing machine (Model 1122, Instron Corp., Canton, Mass.). A melon was placed between and perpendicular to the crosshead uprights, resting on its long side on a flat table. The loading device on the crosshead was a flat plate [15 cm (6 in.) dia.]. Force-deflection was recorded at a crosshead speed of 5mm/min (0.2 in./min) up to a fixed deflection of 2.5 mm (0.1 in.). Slope of the force-deflection curve, between 0.5 and 2.5 mm, and the force at 2.5 mm (0.1 in.) deflection (F@2.5) were recorded. The curve was linear except in the region of 0.0 to 0.5 mm and thus this portion of the curve was not used. The melon was horizontally rotated 90° from the original position and tested again at the same spot for the second reading. Data analysis used the average of the two readings for Slope and F@2.5for each fruit.

Acoustic measurements were taken with the device developed by Farabee and Stone (1991) (fig. 1). The probe consisted of a closed end, Plexiglas cylinder approximately 5 cm (2 in.) in diameter and 15 cm (6 in.) long. A thin, disk-shaped ceramic piezoelectric element, bonded to a similar sized thin brass disk, was mounted at the end of the cylinder in contact with the melon. A solenoid, inside the cylinder, was used to deliver a mechanical impulse to the flat face of the piezo ceramic. The impulse was transferred by the ceramic to the watermelon and in turn, the resulting

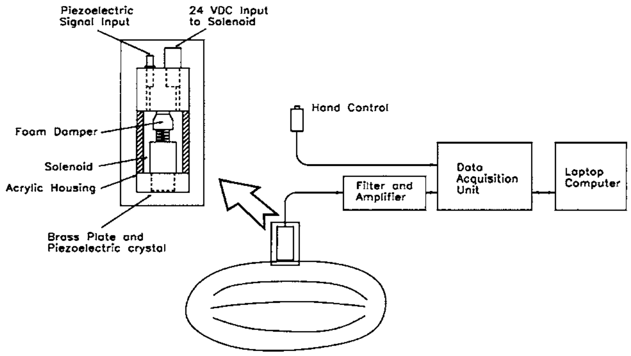

Figure 1–Schematic of impulse response instrumentation.

vibration of the melon drove the piezo ceramic 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. Data sampling was performed with a data acquisition unit (I/O Tech model 100, Cleveland, Ohio). The acoustic signal sampling frequency was 5000 Hz (1024 pts) with 12 bit precision. An Intel 486 based PC was used to process data and control the operation of the data acquisition unit. 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. A Fast Fourier transform of the data was normalized using the frequency with the largest amplitude. Acoustic measurement locations were at the mid-section of the melon; one was on the top of the melon, opposite the impact point, the other two were approximately 120° either direction from the top, around the circumference. The spectrum for a typical melon prior to dropping and after five drops indicates that resonant modes may have changed in amplitude or shifted in frequency following mechanical damage (fig. 2).

Multiple acoustic parameters were evaluated for spectral characterization. These parameters were BM_1, BM_2, BM_3, BM_4, BM_5, BM_6, BM_7, and CFN50 where BM signifies the band magnitude and CFN signifies center frequency. BM values were calculated by summing the normalized

Table 2. Band magnitude variables and their encompassing frequency range

BM_1	BM_2	BM_3	BM_4	BM_5	BM_6	BM_7
40-90 Hz	60-110 Hz	70-120 Hz	80-130 Hz	85-160 Hz	100-180 Hz	120-200 Hz

spectrum magnitudes within a specified bandwidth and dividing by the sum of spectrum magnitudes between 0 and 500 Hz (table 2). These values were proportional to the energy content between the band width 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, from 0 to 500 Hz, to find the narrowest frequency band that contained 50% of the total energy of the spectrum. The bandwidths associated with the BM parameters were based on the previous study by Stone et al. (1996). These bandwidths were chosen so that they overlapped each other and were concentrated on frequencies which were visually observed from spectral plots to be the most dynamic. The three impulse measurements for each melon (parameters $BM_{1\text{-}7}$ and CNF50) were averaged for data analysis.

Results and Discussion

Internal Damage

Damage of varying degrees was visually observed in all melons after five drops and was characterized by the separation of the central part of the melon from the seeded flesh (fig. 3). Cracks or flesh separation also occurred between the rind and the seeded flesh. In most cases, damage was considered severe because the separations were complete with gaps between adjacent areas. No attempt was made to quantify damage due to the difficulty in specifying parameters such as crack length or width. No known disorders such as hollow-heart were present in the melons tested.

Compression Parameters

Compression measurements for all melons and all drops showed a strong relationship (r = 0.992) between Slope and force at 2.5 mm (0.1 in.) deflection (F@2.5). This relationship was expected because the force-deformation curve was nearly linear and thus the dependence between these two parameters were obvious. Mean compression parameters of Slope and F@2.5 for each treatment

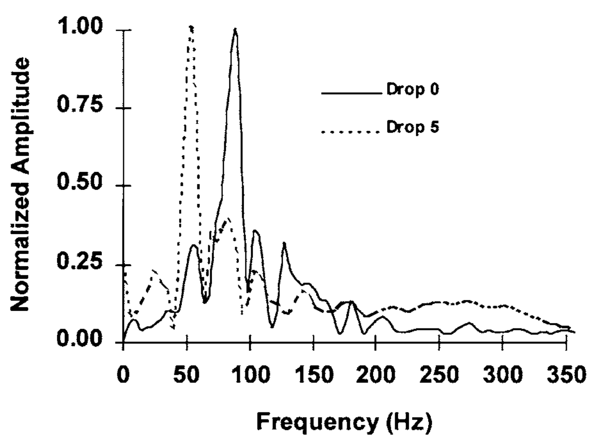

Figure 2–Normalized spectral amplitude obtained from two measurements of a melon prior to dropping and after being dropped five times from 25 cm (10 in.).

64%
lines for position only

Figure 3–Cross-section of watermelon showing internal damage sustained after five drops from 25 cm (10 in.).

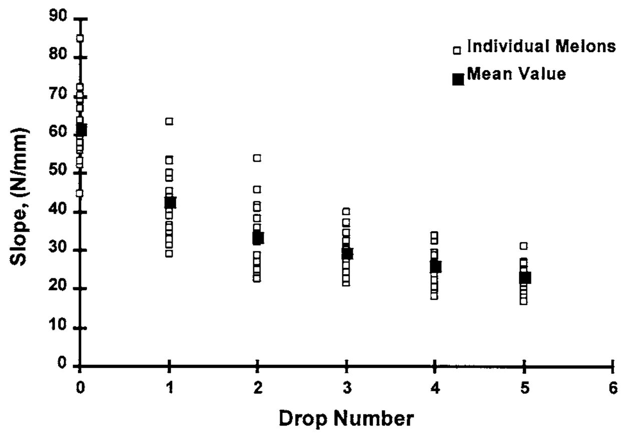

Figure 4–Slope obtained from Instron compression tests for melons at each drop number.

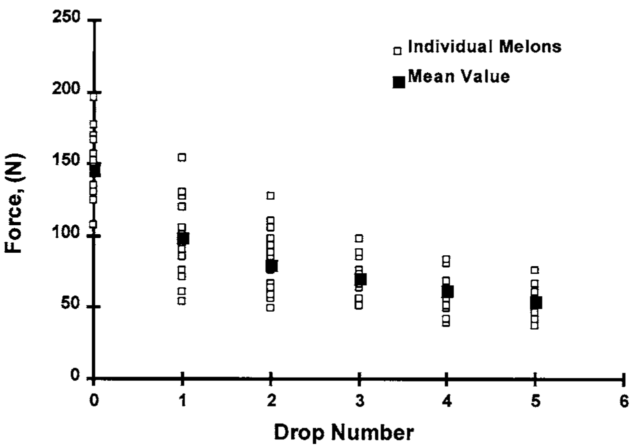

Figure 5–F@2.5 obtained from Instron compression tests for melons at each drop number.

(dropped and undropped) showed a monotonic decline in Slope and F@2.5, figures 4 and 5, respectively. Contiguous means of Slope and F@2.5 for drop numbers 0, 1, and 2 were statistically different (single factor ANOVA, α = 0.05) while means at higher drop numbers were not always different. These observations would thus seem to indicate that these parameters gave a reasonable indication of internal melon condition.

The decline in compression values for individual melons was similar to that for the mean values, i.e., in no case did values increase after a drop. The maximum of individual Slope and F@2.5 values though, was almost double the minimum value. After multiple drops this spread became smaller. The wide variation in individual values for each treatment creates considerable ambiguity between undropped and dropped melons and reduces the value of these parameters as criteria for sorting by internal status. The variation for undropped melons may also indicate that compressive stiffness is also dependent on the internal structure and the physical dimensions of each melon.

Correlation Between Acoustic and Compression Parameters and Drop Number

Correlation between acoustic parameters and Slope was examined to determine which acoustic parameters might have potential as a predictor of internal status. Slope was used as a quantifier of damage because mean Slope values consistently declined following drops known to cause internal damage. Multiple Linear Regression was performed between Slope and the $BM_{1\text{-}7}$ parameters, CN50 and mass. A best model was selected based on the maximum adjusted R^2 value using combinations of the dependent variables. The model coefficients are shown in table 3. Based on the model selection criteria, BM_1, BM_5, BM_6, CFN50, and mass were excluded from the model. Slope values predicted from the BM parameters and measured Slope values are plotted in figure 6. Predicted Slope versus drop number has similar characteristics to measured Slope versus drop number (fig. 7). Predicted Slope means at drop numbers 0, 1, and 2 were statistically different (single factor ANOVA, α = 0.05). The selection of Slope would appear to have provided a reasonable estimation of internal damage based on the consistent mean decline in these values after each drop. If these values are actually an accurate measurement of internal damage then the acoustic measurements could be a reasonable estimator of internal structure based on multiple linear regression results. Slope values, though, showed a wide variation for melons before dropping and after one drop which indicates they may only be partially influenced by internal breakage. Differences in individual melon structure and size

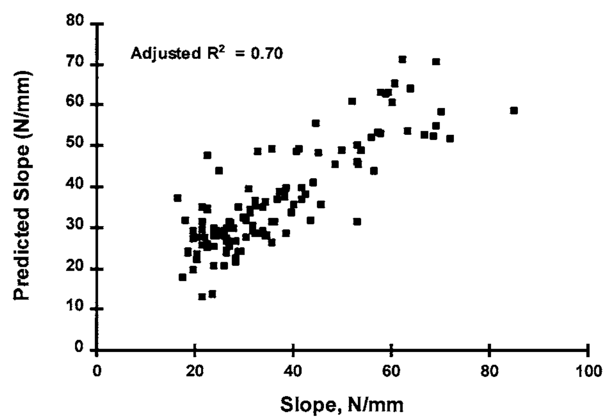

Figure 6–Predicted slope values vs measured slope for all melons at each drop number.

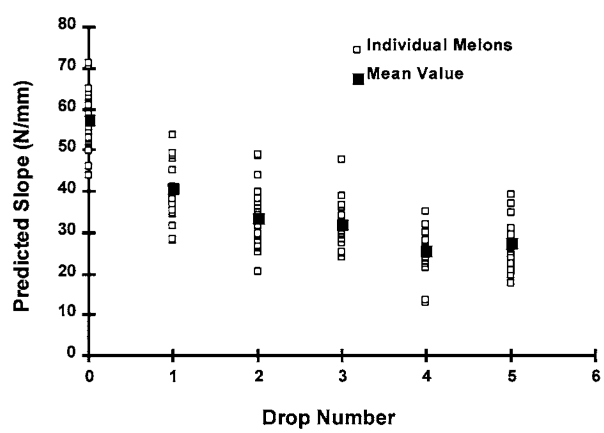

Figure 7–Individual and mean of predicted slope values for all melons at each drop number.

apparently may have to be accounted for in order to achieve accurate measurements with either compression tests or the acoustic instrument.

The variation in compression and acoustic values between individual melons makes the development of sorting criteria difficult. In general, undamaged melons were distinguishable from melons that were dropped three to five times. This can be seen in figures 4, 5, and 7 by selecting a cut-off value that includes all undamaged melons but excludes most or all of the melons at higher drop numbers. Sorting large numbers of melons under commercial conditions would thus result in a percentage of false accepts or rejects. By assuming a normal distribution of the data at each drop for the Predicted Slope values (fig. 7), a cut-off value equal to 40 would result in 0.90 % of false accepts and 1.13% of false rejects for melons dropped 5 times and melons not dropped, respectively. These values were obtained by normalizing the data distribution at each drop number and determining $P[Z < z]$ ($z = 40$) from a standard normal probability table. Drop numbers less than five, under the conditions of this study, would have a greater number of false accepts.

Conclusions

Mean Slope and F@2.5 values decreased significantly after each drop, indicating that either measurement estimates the degree of internal damage in watermelon. The variation in these measurements at a given drop number indicates they may be also influenced by other factors such as individual melon structure and size. This was similarly true for the BM acoustic parameters.

While reasonable correlation was found between Slope measurements and BM parameters, the acoustic parameters could only resolve between large differences in internal damage. To detect small differences would require diminishing other factors that affect both the acoustic and compression measurements.

A more accurate and easy way to assess internal damage in watermelon is needed. Cutting melons open and measuring or visually ranking internal damage would require a large number of melons for statistical significance. Non-invasive imaging techniques, although expensive, could potentially be used to estimate total crack length or total internal void space.

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 Technol.* 22(5):635-646.

Allred, A. J. and G. Lucier. 1990. The U.S. watermelon industry. USDA. Economic Research Service Staff Report AGES 9015. Washington, D.C.: USDA.

Chen, H., J. Debaerdemaeker and V. Bellon. 1996. Finite element study of the melon for nondestructive sensing of firmness. *Transactions of the ASAE* 39(3):1057-1065.

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.

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.

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

Yamamoto, H., M. Iwamoto and S. Haginuma. 1981. Nondestructive acoustic impulse response method for measuring internal quality of apples and watermelons. *J. Japanese Soc. Hort. Sci.* 50(2):247-261.

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

Stone, M. L., P. R. Armstrong, X. Zhang, G. H. Brusewitz and D. D. Chen. 1996. Watermelon maturity determination in the field using acoustic impulse impedance techniques. *Transactions of the ASAE* 39(6):2325-2330.

The Packer. 1994. The Packer's 1995 fresh trends. 101(54):45, 76.