Nondestructive Sonic Measurement of Kiwifruit Firmness

Judith A. Abbott¹ and David R. Massie²

Instrumentation and Sensing Laboratory, Agricultural Research Service, United States Department of Agriculture, Beltsville, MD 20705

ADDITIONAL INDEX WORDS. *Actinidia deliciosa*, instrumentation, postharvest handling, quality, texture

ABSTRACT. Firmness is a critical quality characteristic in kiwifruit [*Actinidia deliciosa* (A. Chev.) C.F. Liang et A.R. Ferguson] marketing. The industry seeks a nondestructive method for firmness sorting. We measured sonic vibrational responses of 149 kiwifruit over the range 0 to 2000 Hz and compared them with Magness-Taylor (MT) penetrometer values. Sonic resonant frequencies and mass were combined to calculate a sonic stiffness coefficient. Coefficients of determination (r^2) for sonic stiffness coefficients versus MT slope and log of MT maximum force were 0.88 and 0.86, respectively. Sonic stiffness coefficients provided good to excellent classification of kiwifruit into two or three firmness categories based on MT maximum force values. A combination of amplitudes at several specific sonic frequencies selected by stepwise discriminant analysis or regression tree analysis also provided successful sorting algorithms. Identification of soft kiwifruit was 89% to 96% accurate and of firm kiwifruit 83% to 91%. These conclusions are based on a rather small sampling of kiwifruit of a single source and size, but the results clearly indicate the potential of a nondestructive firmness measurement based on sonic frequency vibrations.

As kiwifruit have become more familiar to consumers and more plentiful, market competition and the requirement for high quality have increased. Firmness is a critical quality characteristic in the marketing of kiwifruit, as it is for most fresh fruit and vegetables. Currently, firmness of a lot of kiwifruit is measured destructively by puncturing a representative sample from the lot with a Magness-Taylor (MT) fruit firmness tester or equivalent penetrometer, such as the Effe-gi. MT is usually measured with the 7.9-mm MT probe at two sites around the midlength of each fruit, skin removed, with the first site either selected randomly or on a relatively flat side and the second site, opposite the first. New Zealand Kiwifruit Marketing Board standards for export specify that fruit be at 0 to 5 °C and that a 2-mm-thick slice of skin from the median of the fruit be removed; however, fruit orientation is not specified.

The MT test as currently applied only estimates the average firmness of a lot. The destructive nature of the test limits the size of the sample taken. Because of the variation in firmness within a grower lot of fruit, the industry needs a firmness sorting method.

Several alternative methods for firmness measurement of kiwifruit have been reported recently. Studman and Yuwana (1992) reported that a destructive twist test that measures the crushing strength of the flesh correlated better with soluble solids content (an indication of ripeness) in kiwifruit than Effe-gi penetrometer values. Fan et al. (1994) and Hung and Prussia (1995) evaluated a nondestructive laser-puff firmness detector for several horticultural products, including kiwifruit. Takao and Ohmori (1994a, 1994b) and Yakushiji et al. (1995) reported the development of benchtop and hand-held nondestructive fruit firmness testers suitable for kiwifruit. In the laser-puff detector and the instruments

reported by Takao, firmness is based on deformation under a specific load within the elastic range of the fruit so that no bruising occurs. The hand-held firmness meter reported by Takao was developed mainly for measuring kiwifruit firmness. Abbott and Massie (1995) tested kiwifruit with a nondestructive dynamic force-deformation device and reported a relationship to MT firmness of $r^2 = 0.83$. McGlone and Schaare (1993) and Patel et al. (1993) reported on three impact firmness instruments, including a benchtop inspection instrument and an automated sorter. Results on kiwifruit showed a strong relationship between dwell time and penetrometer measurement ($r^2 = 0.83$). Packing house trials of their automated sorter on kiwifruit resulted in $\approx 17\%$ misclassification of firm fruit compared with 11% with hand sorting.

There has been considerable research on nondestructive measurement of firmness of fruits and vegetables, especially of apples (*Malus domestica* Borkh.) and peaches [*Prunus persica* (L.) Batch]. The dominant textural attribute of whole kiwifruit seems intuitively (to the authors) to be stiffness rather than strength (resistance to flexing and to crushing, respectively). The sonic resonant frequencies of a body are related to its elastic properties (e.g., stiffness), its size and shape, and its density. Clark and Mikelson (1942), Abbott et al. (1968), Finney (1972), Yamamoto et al. (1980), Armstrong et al. (1990), Affeldt and Abbott (1992), and others have proposed using sonic resonant frequencies of intact fruit to estimate texture and maturity. Cooke and Rand (1973) extended the theory of elastic vibration for three concentric spheres to resonant behavior of apples. The three-concentric-sphere model corresponds to the three concentric layers of fruit tissue: exocarp (skin), mesocarp (flesh), and endocarp (core). The mesocarp is of greatest interest because it constitutes most of the edible portion. The theory for vibration of an elastic sphere assumes that the object is approximately elastic for small deformations and, of course, that it is spherical. Tissues of most fruit are viscoelastic but generally have been assumed to be elastic at very small deformations. Although a kiwifruit is certainly not as spherical as many apples and there is no certainty that Poisson's ratio remains constant, we felt that it was close enough that the theory for spherical modes of vibration was loosely applicable. Resonant frequency of a sphere is related to its Young's modulus (stiffness) by the following formula:

Received for publication 20 Nov. 1996. Accepted for publication 8 Oct. 1997. We recognize I. Warrington, New Zealand Dept. of Scientific and Industrial Research, for asking the germinal question and C. Richardson, New Zealand Kiwifruit Marketing Board, for supplying the kiwifruit. Use of trade names is for information only and does not imply endorsement of the product named or criticism of similar ones not named. The cost of publishing this paper was defrayed in part by the payment of page charges. Under postal regulations, this paper therefore must be hereby marked *advertisement* solely to indicate this fact.

¹Present address: Horticultural Crops Quality Laboratory, ARS, USDA, Beltsville, MD 20705.

²Present address: Foss NIRSystems Inc., 12101 Tech Road, Silver Spring, MD 20904.

$$E = b_i f_i^2 m^{2/3} \rho^{1/3} \quad [1]$$

where E is Young's modulus, b is a combined constant, i is a designated resonant mode, f is resonant frequency, m is mass, and ρ is density (Cooke, 1972). The value of ρ is usually assumed to be constant, as it varies little in mature fruit within a cultivar or species. Eliminating constants from the equation leaves f^2 and $m^{2/3}$. Abbott et al. (1968) proposed a stiffness coefficient calculated as $f^2 m$ for fruit and vegetables. Cooke (1972) proposed the more fundamentally based $f^2 m^{2/3}$ for the stiffness coefficient of approximately spherical commodities. Simulation studies of nonspherical fruit such as apple, peach, pineapple (*Ananas comosus*), and watermelon (*Citrullus lanatus*) have shown that the stiffness coefficient $f^2 m^{2/3}$ is approximately linearly related to the elastic modulus (Chen and De Baerdemaeker, 1993a, 1993b, 1993c; Chen et al., 1992; Lu and Abbott, 1996, 1997; Rosenfeld et al., 1992, 1993; Wu et al., 1994). We believed that kiwifruit should respond similarly enough for sonic sorting to be commercially possible.

The objective of this study was to test on kiwifruit nondestructive sonic resonance techniques that are being developed for apple firmness testing (Abbott et al., 1992, 1995; Affeldt and Abbott, 1992).

Materials and Methods

KIWIFRUIT. Two lots of kiwifruit were obtained from the same grower in California. The fruit were commercially sorted and packed. Randomly selected flats of size 33 kiwifruit (i.e., 33 fruit per standard flat) were air shipped to Beltsville, Md., immediately after harvest. We received 99 fruit from an early harvest and 66 fruit from a late harvest (15 Oct. and 3 Dec. 1991, respectively). All fruit were immediately placed in a 0 °C storage room equipped with an ethylene scrubber (Purafil, Kamapell Rogers Co., Bethesda, Md.). Initial measurements were completed within 3 d after receipt. We recorded initial mass and dimensions. Kiwifruit are generally oval in cross-section so we recorded minimum and maximum diameters and length of the stem-blossom axis. The mass was measured again on the day of sonic testing just before MT measurement and was used to compute the stiffness coefficient. Fruit were then measured at weekly intervals.

Because the temperature of the fruit is known to affect MT firmness values and the industry generally is concerned with measurement of fruit at temperatures near the 0 °C storage temperature, we attempted to keep fruit near 0 °C. Fruit were taken from storage in their commercial trays immediately before measurement by each method, the plastic film liner was replaced over remaining fruit within the tray to furnish some insulation after each specimen was removed, and the tray was returned to 0 °C between test methods.

On each successive measurement date, sonic transmittance was measured on intact fruit, along with other measurements not reported here (Abbott and Massie, 1995). For the early harvest, we remeasured sonic transmission on all remaining intact fruit and sacrificed 16 or 17 fruit for MT each time. From the late harvest, we measured only the 16 fruit preselected for MT on each successive measurement date to eliminate the possibility of softening caused by handling and warming during repetitive measurements. Testing was otherwise the same.

SONIC TRANSMITTANCE TEST. Each kiwifruit was mounted horizontally on a pedestal attached to an electromagnetic vibrator. Measurements were made perpendicular to the stem-blossom axis through the minimum diameter and then through the maximum

diameter. A pad of floral clay (≈ 3 cm in diameter) on the pedestal was shaped to cradle an average kiwifruit, but care was taken not to allow the clay to adhere to the fruit. The vibrator was pulsed with a sinc(t) pulse [i.e., $\sin(t)/t$, where t is time] containing all frequencies up to 2000 Hz, with equal energy density at each frequency (Abbott et al., 1992). An accelerometer mounted on a flexible membrane was held mechanically against the top of the fruit to detect movement. A signal analyzer converted the accelerometer signals to the frequency domain and then averaged the results of 10 pulses. That average frequency spectrum was recorded at 5-Hz increments. Frequencies of the peaks were found later by computer, verified manually, and corrected if necessary.

MT FIRMNESS. The MT firmness test was made using a 7.9-mm MT probe (Ballau Manufacturing Co., Laurel, Md.) mounted in a universal testing machine interfaced to a personal computer. Crosshead position was controlled by computer and was tracked in 0.0254-mm increments by an optical encoder attached to the drive screw of the testing machine. Punctures were made at 2.1 mm·s⁻¹ (5 inch/min) at thinly pared sites on opposite sides at the minimum diameter and then at the maximum diameter. Many forces, distances, slopes, and areas were extracted from the recorded force/deformation (F/D) records. FMAX is the maximum force registered at any penetration distance ≤ 7.9 mm ($\leq 5/16$ inch, to the inscribed line on the standard MT probe) and is essentially the value read from manual MT devices. FFULL is force at full penetration (7.9 mm). WFULL is the work or total energy under the curve to FFULL. Slopes were calculated as follows:

$$M_i = [(F_{i+2} + F_{i+3}/2) - (F_{i-2} + F_{i-3}/2)] / (5 \times 0.0254 \text{ mm}) \quad [2]$$

where M is slope, i is datapoint number (increments of 0.0254 mm or 0.001 inch), and F is force at the specified datapoint. We determined and analyzed the slopes at several locations, including slope at 0.2 and 0.5 mm ($M@0.5\text{mm}$), slope at half the rupture force, maximum slope to the rupture point, chordal slope to FMAX, and others.

STATISTICAL DESIGN AND ANALYSIS. The two harvests were combined for analysis ($n = 149$); harvests and storage durations were used only to provide a range of firmness. Measurements through the minimum and maximum diameters were analyzed separately. Because there was little difference in relationships among measurements between the two sets, only data from the minimum diameter are reported. Comparisons between firmness measurements were made with standard regression analyses (SAS, 1989). Because of nonlinearity of the regressions apparent in scatter plots (not shown), MT values were converted to $\log_{10}$. Regression analyses were performed on the original and the transformed data. MT maximum force is an industry standard, so we considered FMAX to be the reference measurement for classification, with the two-class case divided at 14.7 N (1.5 kgf) and the three-class case separated at 9.8 and 14.7 N (1.0 and 1.5 kgf, respectively), limits for shipment often used by the kiwifruit industry. Algorithms to classify fruit into firmness categories were developed by successively applying stepwise discriminant analysis and discriminant analysis (SAS, 1989) and by applying classification tree analysis (Breiman et al., 1984; Steinberg and Colla, 1995) using CART Classification and Regression Trees software (California Statistical Software, Inc., Salford Systems, San Diego, Calif.).

Classificatory discriminant analysis is used to classify a sample into one of several groups based on one or more quantitative variables. Discriminant analysis develops a discriminant function for classifying observations based on generalized squared distance; each observation is placed in the class from which it has the smallest generalized squared distance (SAS, 1989). The discriminant function is based on the pooled covariance matrix. In stepwise

discriminant analysis, the variable with the greatest discrimination power based on Wilk's lambda (a multivariate F statistic) is entered into the model. At each successive step, the best additional variable is entered and the model is examined. If the Wilk's lambda for the variable that contributes least to the discriminatory power of the model is not significant, the variable is removed. Another variable is added and the model is reevaluated. When all variables in the model meet the criterion to stay and none of the other variables meets the criterion to enter, model building stops. We built the stepwise model with data for 0 to 2000 Hz and mass, using significance levels of 0.15 to enter and to stay. We then used the variables selected by the stepwise procedure to develop a classic discriminant function.

Unlike discriminant analysis, which combines weighted values of several variables into a single classifier value, CART develops a decision tree by binary recursive partitioning. The decision tree is similar to taxonomic trees in that each split is based on the answer to a yes or no question. Each group of samples is split into two new groups or child nodes based on the values of one variable. Each child node is then examined for further splitting by other input variables until no further partitions are possible (all samples belong to a single class or no input variable can be found to further separate them). CART is a procedure that can be used to analyze either categorical (classification) or continuous data (regression). The tree begins with all input cases in the root node and successively splits them into pairs of child nodes. Some nodes are terminal, i.e., the final classification has been determined, and others are further split using additional key determinants. For example, in our analysis, fruit with amplitudes less than or equal to -62.78 dB at 1525 Hz were classed as soft, but fruit with greater amplitudes at 1525 Hz could be either intermediate or firm. The indeterminate node was split on the amplitude at 2000 Hz. CART looks at all possible splits for all variables and then ranks each splitting rule on a goodness-of-split criterion, usually a measure of how well the cases in the parent node were classed. It then repeats the search process on each child node. The process continues until further splitting is impossible (only one case or identical cases) or is stopped by some other rule. All cases within the node are assigned to a single class, usually the class occurring with the greatest frequency within the group. Note that there may be multiple nodes, determined by the values of different variables, that belong to a single class. The tree with the maximum possible number of splits is developed, pruned to yield several alternative trees, and then the best tree is determined by considering error rates and costs. When the dependent variable is continuous, CART generates a classification tree where terminal nodes represent predicted values instead of classes; however, we used the categorical mode and assigned target classes of 0 or 1 (or 0, 1, 2 for three categories) based on measured MT values. The model is cross-validated against 10 subsets comprising 9/10s of the original data.

Results and Discussion

KIWIFRUIT. Although only maximum force is normally reported for the MT test, we examined the entire F/D record (Fig. 1A). No bioyield point was expected in a noncrisp fruit, and none was found. The maximum force invariably occurred at rupture, and it occurred considerably before full penetration. FMAX ranged from 4 to 57 N. WFULL is an integration of the energy or work put into penetration and may be a better measure of overall firmness than maximum force when the depth of maximum penetration is well controlled.

Although horticulturists define fruit firmness as the maximum

force in MT penetration regardless of the penetration at which that occurs, engineers usually relate firmness to stiffness, as indicated by Young's modulus or approximated by the slope of the F/D curve. We believe that consumers most likely test kiwifruit stiffness, rather than strength, when they flex their hands to gently squeeze the fruit. Kiwifruit flesh is viscoelastic and it displays different slopes along the F/D curve (Fig. 1A) before failure. After statistical analyses, we selected the slope M@0.5mm as the destructive stiffness measurement to report. The other slopes generally gave insignificantly lower r^2 values with sonic measurements, generally differing by ≤ 0.01 . Our sonic test values are compared to both measures of firmness (FMAX and M@0.5mm) in Table 1.

SONIC TRANSMITTANCE TEST. Typical sonic transmittance curves for kiwifruit are shown in Fig. 1B. The initial peak, at ≈ 300 Hz, contains the first resonance of the fruit. However, this resonance is likely a single-degree-of-freedom vibration system, with the bulk of the fruit forming the rigid-body-mass (Yong and Bilanski, 1979); it was therefore ignored. Within the sonic frequency range we examined, each fruit had a single broad resonance, peaking at 460 to 1605 Hz. We took the point of maximum amplitude as the resonant frequency. The resonant frequency of the kiwifruit generally decreased with successive storage times (Fig. 1B) as expected.

The feature of the sonic transmittance curves simplest to detect is amplitude at a fixed frequency. Amplitude at any one specific frequency did not correlate well with MT values (data not shown),

Fig. 1. Typical Magness-Taylor force-deformation curves (A) and sonic spectra (B) for kiwifruit during storage at 0 °C for 0 or 30 d (bold and light lines, respectively).

Table 1. Coefficients of determination (r^2) between sonic resonant frequency (f) or stiffness coefficients (f^2m or $f^2m^{2/3}$) and Magness-Taylor force and deformation data for California kiwifruit from combined early and late harvests in 1991 ($n = 149$).

Magness-Taylor variables ^z	Sonic resonance		
	f	f^2m	$f^2m^{2/3}$
FMAX	0.62	0.74	0.72
FFULL	0.67	0.77	0.76
WFULL	0.66	0.77	0.76
M@0.5mm	0.81	0.88	0.88
log FMAX	0.83	0.88	0.86
log FFULL	0.88	0.92	0.90
log WFULL	0.86	0.90	0.90
log M@0.5mm	0.86	0.88	0.86
Mass	0.10	NA ^y	NA

^zFMAX = maximum force attained, FFULL = force at maximum penetration, WFULL = work or energy to maximum penetration, M@0.5mm = slope at 0.5 mm penetration.

^yNA = Not appropriate because mass is a component of the value.

nor did amplitude at the resonant frequency of each kiwifruit ($r^2 \leq 0.35$). This also has been reported for apples (Abbott et al., 1992). Amplitude depends on the quality of the contacts between fruit and vibrator and between fruit and accelerometer. For this reason, sonic spectra need to be normalized before analysis by methods that depend on amplitudes, such as CART, so that relative amplitudes are used. Our preferred method—detecting resonant frequencies—requires only that sufficient contact be made to transmit the impulse well enough to induce detectable resonant peaks. Improving the contact increases the resonant amplitudes but does not generally change the resonant frequency. We specifically did not try to bond or enhance contacts because it is unlikely that this could be done in a high speed sorting instrument for packing houses or even in routine inspection instruments.

The next feature we analyzed was resonant frequency (f) (Table 1). According to material properties theory, resonant frequency is related to stiffness. We also expected it to be related to failure strength and, indeed, f was closely related to MT FMAX and similarly to FFULL and WFULL (Table 1). Because plots of FMAX versus resonant frequency or stiffness coefficient were curvilinear, we also correlated sonic data to log-transformed F/D data (e.g., Fig. 2A). The logarithmic function improved the linear relationship with force and energy values (Table 1). However, the resonant frequency was much more closely related to slope of the MT curve (stiffness) at any of the several slopes we examined, for example M@0.5mm, than to the force at rupture or maximum penetration (Table 1, Fig. 2B vs. Fig. 2A), in accordance with theory. Transforming slopes to logarithms did not improve r^2 values.

Fruit mass, dimensions, and density are related to resonant frequency by material properties theory. However, there was little correlation between fruit dimensions or mass and resonant frequency in this data set (Table 1), probably because of the extremely narrow range encompassed within one packing size. Nevertheless, it is likely that mass would influence the resonant frequencies over a wide range of sizes. The stiffness coefficients derived for apples (Abbott et al., 1968; Cooke, 1972) include correction for mass. Applying either stiffness coefficients (f^2m or $f^2m^{2/3}$) significantly improved ($P \leq 0.05$) the coefficients of determination (r^2) (Table 1) more than using resonant frequency alone. The r^2 values for f^2m were consistently better than those for $f^2m^{2/3}$, but the differences were not significant. The $f^2m^{2/3}$ is more theoretically based, at least for a spherical fruit, therefore we used $f^2m^{2/3}$ for classification

analyses. A mass adjustment reflecting the ovoid shape of kiwifruit might further improve the relationships, but it was not our intent to test this concept and, further, we did not have fruit of sufficiently different shape and size to develop an adequate geometric model.

In sensory tests of consumer-ready kiwifruit, Stec et al. (1989) divided fruit into firmness categories by MT value. In one test, soft was 4.4 to 6.4 N and firm was 6.4 to 8.8 N; in a second test, soft was 3.9 to 5.9 N, firm was 5.9 to 7.8 N, and hard was 7.8 to 9.8 N (converted from kgf). Fruit must, of course, be firmer for shipment. A cutoff firmness of 14.7 N is desired, with a tolerance for >9.8 N. We evaluated the ability of sonic measurements to classify kiwifruit into two or three categories (based on 9.8 and 14.7 N) using two statistical approaches: discriminant analysis and classification trees (Table 2). Measurements made through the minimum and maximum diameters were similar (data not shown), but the minimum diameter gave very marginally higher percent correct discrimination. It is likely that kiwifruit would naturally repose with the minimum diameter vertical and that measurement might be

Fig. 2. Relationship of sonic stiffness coefficient $f^2m^{2/3}$ to Magness-Taylor firmness (maximum force) (A) and slope (M@0.5mm) (B). Conversion factors for SI force units: 1 N (Newton) = 0.1020 kgf = 0.2248 lbf.

made vertically, so only data for the minimum diameter are shown.

Discriminant analysis for a two-category classification selected as optimal a combination of mass and amplitudes at seven frequencies throughout the spectrum. That solution accepted the fewest soft fruit (7% of those with actual MT <14.7 N) and the most firm fruit (91%), and so might be economically the best solution. Discriminant analysis using only the stiffness coefficient did nearly as well at rejecting soft kiwifruit (8% incorrectly accepted) but misclassified more of the firm fruit (17% rejected and 83% accepted). However, the classification tree based on the stiffness coefficient alone had the highest accuracy in identifying soft kiwifruit (only 4% incorrectly accepted), with the same 83% acceptance of firm kiwifruit.

A three-category classification would allow the packer to choose whether to accept (pack), resort, or reject fruit in the marginal intermediate category, depending on economics and risk of rejection by the receiver. For three categories, discriminant analysis gave excellent classification using amplitudes at thirteen frequencies and mass. The stiffness coefficient alone in discriminant analysis also gave good separation of soft and firm fruit but did poorly on intermediate fruit. The classification tree based on the stiffness coefficient alone was effective and is the simplest model.

Many factors must be considered in selecting a classification scheme, and this test is not comprehensive enough to be conclusive. We favor the stiffness coefficient by which to sort because it represents a fundamental relationship between sonic vibrational behavior and firmness and because it is simpler to adjust the

precise cutoff value of a single variable than to adjust an algorithm, which includes several spectral variables. However, the approach using relative amplitudes at several frequencies in discriminant analysis would be economically superior for sorting this particular group of kiwifruit; i.e., it rejected fewest of the firm fruit while still rejecting a large percentage of the soft fruit. Of course, we recognize that the specific frequencies selected by either discriminant analysis or CART would differ with different sets of fruit. Using relative amplitudes at several frequencies would require more care to ensure consistent input signals and consistent driver-fruit and fruit-detector contacts even if curves were normalized. The frequencies selected might also vary among seasons and grower lots. In other words, the multifrequency method is more empirical and more variables may affect it than the more fundamental method. Before commercial implementation, a more robust model would have to be developed by testing far more fruit than were included in this test. It is likely that models would need to be adjusted locally and seasonally; however, automated sorting instruments are commonly adjusted to local conditions and seasonal variations.

These conclusions are based on a small sampling of kiwifruit of a single source and size, but the results clearly and strongly indicate the potential of a nondestructive firmness measurement based on sonic frequency vibrations. The selection of statistical methods for developing sorting rules needs to be further evaluated with larger, more varied samples and with consideration of economic factors and ease of use.

Table 2. Two- and three-category classification of kiwifruit using the sonic stiffness coefficient $f^2m^{2/3}$ or amplitudes at selected frequencies.

Analysis method	Classification scheme	Actual MT-based class ^z	Percent classified as		
			Soft	Intermediate	Firm
Two-category classification					
Discriminant analysis	Sonic spectra ^y	Soft	93	---	7
		Firm	9	---	91
Discriminant analysis	Stiffness coefficient $f^2m^{2/3}$	Soft	92	---	8
		Firm	17	---	83
Classification tree	Sonic spectra ^x	Soft	90	---	10
		Firm	14	---	86
Classification tree	Stiffness coefficient $f^2m^{2/3}$	Soft	96	---	4
		Firm	17	---	83
Three-category classification					
Discriminant analysis	Stiffness coefficient $f^2m^{2/3}$	Soft	95	5	0
		Intermediate	25	43	32
		Firm	6	8	86
Discriminant analysis	Sonic spectra ^w	Soft	89	11	0
		Intermediate	0	86	14
		Firm	3	6	91
Classification tree	Sonic spectra ^v	Soft	82	16	2
		Intermediate	4	86	11
		Firm	0	20	80
Classification tree	Stiffness coefficient $f^2m^{2/3}$	Soft	89	11	0
		Intermediate	0	89	11
		Firm	6	11	83

^zTwo-category classification was based on Magness-Taylor maximum force with 84 soft (<14.7 N) and 65 firm (≥14.7 N) kiwifruit; three-category classification had 56 soft (<9.8 N), 28 intermediate, and 65 firm kiwifruit (>14.7 N). Percent soft classed as firm represents incorrect acceptance of soft fruit, percent firm classed as soft represents incorrect rejection of firm fruit, etc.

^yFrequencies selected by stepwise discriminant analysis: 5, 10, 355, 960, 980, 1265, and 1985 Hz, and mass. Frequency spectra were recorded from 0 to 2000 Hz in 5-Hz increments. Actual data were normalized amplitudes at those selected frequencies (also applies to x, w, and v below)

^xFrequency selected for regression tree by CART: 1970 Hz.

^wFrequencies selected by stepwise discriminant analysis: 5, 10, 160, 530, 785, 865, 985, 1070, 1250, 1740, 1760, 1875, and 1990 Hz, and mass.

^vFrequencies selected for regression tree by CART: 1525 and 2000 Hz.

Literature Cited

- Abbott, J.A., N.F. Childers, G.S. Bachman, J.V. Fitzgerald, and F.J. Matusik. 1968. Acoustic vibration for detecting textural quality of apples. *Proc. Amer. Soc. Hort. Sci.* 93:725-737.
- 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.* 117:590-595.
- Abbott, J.A. and D.R. Massie. 1995. Nondestructive dynamic force/deformation measurement of kiwifruit firmness (*Actinidia deliciosa*). *Trans. Amer. Soc. Agr. Eng.* 38:1809-1812.
- Abbott, J.A., D.R. Massie, B.L. Upchurch, and W.R. Hruschka. 1995. Nondestructive sonic firmness measurement of apples. *Trans. Amer. Soc. Agr. Eng.* 38:1461-1466.
- Affeldt, Jr., H.A. and J.A. Abbott. 1992. Agricultural commodity condition measurement. U.S. Patent No. 5,152,401.
- Armstrong, P.R., H.R. Zapp, and G.K. Brown. 1990. Impulsive excitation of acoustic vibrations in apples for firmness determination. *Trans. Amer. Soc. Agr. Eng.* 33:1353-1359.
- Breiman, L., J. Friedman, R. Olshen, and C. Stone. 1984. Classification and Regression Trees. Wadsworth, Pacific Grove, Calif.
- Chen, H. and J. De Baerdemaeker. 1993a. Effect of apple shape on acoustic measurements of firmness. *J. Agr. Eng. Res.* 56:253-266.
- Chen, H. and J. De Baerdemaeker. 1993b. Modal analysis of the dynamic behavior of pineapples and its relation to fruit firmness. *Trans. Amer. Soc. Agr. Eng.* 36:1439-1444.
- Chen, H. and J. De Baerdemaeker. 1993c. Finite-element-based modal analysis of fruit firmness. *Trans. Amer. Soc. Agr. Eng.* 36:1827-1833.
- Chen, P., Z. Sun, and L. Huarng. 1992. Factors affecting acoustic responses of apples. *Trans. Amer. Soc. Agr. Eng.* 35:1915-1920.
- Clark, H.L. and W. Mikelson. 1942. Fruit ripeness tester. U.S. Patent 2,277,037.
- Cooke, J.R. 1972. An interpretation of the resonant behavior of intact fruits and vegetables. *Trans. Amer. Soc. Agr. Eng.* 15:1075-1080.
- Cooke, J.R. and R.H. Rand. 1973. A mathematical study of resonance in intact fruits and vegetables using a 3-media elastic sphere model. *J. Agr. Eng. Res.* 18:141-157.
- Fan, S., S.E. Prussia, and Y.C. Hung. 1994. Evaluating the UGA laser-puff food firmness detector. *Amer. Soc. Agr. Eng.* paper 94-6540.
- Finney, Jr., E.E. 1972. Vibration techniques for testing fruit firmness. *J. Texture Studies* 3:263-283.
- Hung, Y.C. and S.E. Prussia. 1995. Firmness measurement using a nondestructive laser-puff detector, p. 145-154. *Proc. Food Processing Automation IV Conf.*, Chicago, Amer. Soc. Agr. Eng., St. Joseph, Mich.
- Lu, R. and J.A. Abbott. 1996. Finite element analysis of modes of vibration in apples. *J. Texture Studies* 27:265-286.
- Lu, R. and J.A. Abbott. 1997. Finite element modeling of transient responses of apples to impulse excitation. *Trans. Amer. Soc. Agr. Eng.* 40:1395-1406.
- McGlone, V.A. and P.N. Schaare. 1993. The application of impact response analysis in the New Zealand fruit industry. *Amer. Soc. Agr. Eng. Paper* 93-6537.
- Patel, N., V.A. McGlone, P.N. Schaare, and H. Hall. 1993. "BerryBounce": A technique for the rapid and nondestructive measurement of firmness in small fruit. *Acta Hort.* 352:189-198.
- Rosenfeld, D., I. Shmulevich, and G. Rosenhouse. 1992. Three-dimensional simulation of the acoustic response of fruit for firmness sorting. *Trans. Amer. Soc. Agr. Eng.* 35:1267-1274.
- Rosenfeld, D., I. Shmulevich, and G. Rosenhouse. 1993. Three-dimensional simulation of the dynamic response of fruit. *Amer. Soc. Agr. Eng. Paper* 93-6022.
- SAS Institute Inc. 1989. SAS/STAT user's guide. version 6. 4th ed. vol. 1. SAS Inst., Cary, N.C. p. 943.
- Stec, M.G.H., J.A. Hodgson, E.A. MacRae, and C.M. Triggs. 1989. Role of fruit firmness in the sensory evaluation of kiwifruit (*Actinidia deliciosa* cv Hayward). *J. Sci. Food Agr.* 47:417-433.
- Steinberg, D. and P. Colla. 1995. CART: Tree-structured non-parametric data analysis. Salford Systems, San Diego, Calif.
- Studman, C.J. and Yuwana. 1992. Twist test for measuring fruit firmness. *J. Texture Studies* 23:215-227.
- Takao, H. and S. Ohmori. 1994a. Development of device for nondestructive evaluation of fruit firmness. *Jpn. Agr. Res. Quart.* 28:36-43.
- Takao, H. and S. Ohmori. 1994b. Development of device for nondestructive evaluation of fruit firmness. *Jpn. Agr. Res. Quart.* 28:36-43.
- Wu, N., M.J. Pitts, D.C. Davis, and R.P. Cavalieri. 1994. Modeling mechanical behavior of apple with the finite element method. *Amer. Soc. Agr. Eng. Paper* 94-3585.
- Yakushiji, H., S. Ono, H. Takao, and Y. Iba. 1995. Nondestructive measurement of fruit firmness with soft touch sensor in Japanese persimmon (in Japanese). *Bul. Fruit Tree Res. Sta.* 28:39-50.
- 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 evaluation of apples and watermelons. *J. Texture Studies* 11:117-136.
- Yong, Y.C. and W.C. Bilanski. 1979. Modes of vibration of spheroids at the first and second resonant frequencies. *Trans. Amer. Soc. Agr. Eng.* 22:1463-1466.