

# Firmness Measurement of Freshly Harvested 'Delicious' Apples by Sensory Methods, Sonic Transmission, Magness-Taylor, and Compression

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*Additional index words.* *Malus domestica*, quality

**Abstract.** A rapid nondestructive method for measuring apple texture using sonic vibrational characteristics of intact apples was tested on freshly harvested 'Delicious' apples from major U.S. production areas. Sonic transmission spectra and Magness-Taylor (MT) firmness were measured on whole apples and compression measurements were made on excised tissue. Two experienced Agricultural Marketing Service apple inspectors assessed each apple and assigned a ripeness score according to U.S. Dept. of Agriculture grades and standards inspection procedures (based primarily on texture). Sonic functions correlated significantly with ripeness scores, MT firmness, and forces to rupture or crush the tissue in compression. Ripeness scores were more closely correlated with the destructive firmness measurements than with sonic functions. However, sonic measurement has the advantage of being nondestructive, whereas MT and tissue compression are inherently destructive. Further research is needed to modify the Instrumentation and Sensing Laboratory's sonic technique to improve the prediction of apple firmness before it can be adapted for on-line sorting.

Total United States apple production in 1988 was  $>4.1 \times 10^6$  t, valued at \$1.15 billion, with slightly over half marketed as fresh fruit [U.S. Dept. of Agriculture (USDA), 1991]. Effective handling of such a quantity requires sorting for a number of quality and physiological characteristics. Domestic and foreign buyers continuously demand better quality and more uniform ripeness. Texture, particularly firmness, is often used as an indicator of maturity, ripeness, and quality in apples. At present, individual apples cannot be sorted automatically for firmness. The destructive nature of the penetrometer tests [Magness-Taylor (MT) or Effe-gi] commonly used to measure firmness obviously precludes their use for on-line sorting.

Fruit that are relatively rigid can often be judged on their ripeness or firmness by the sound of their resonance when palpitated, as in the traditional watermelon thump test. Many workers have reported basic studies on various aspects of this phenomenon (Liljedahl and Abbott, 1993). Abbott et al. (1968a, 1968b, 1992), Affeldt and Abbott (1989), and Liljedahl and Abbott (1993) reported that resonant frequencies in apples are significantly influenced by changes in fruit maturity or ripeness, size, and condition. Abbott et al. (1968a, 1968b) proposed a stiffness coefficient based on the apple's resonant frequency ( $f$ ) and mass ( $m$ ) to estimate the dynamic elastic properties of the fruit flesh and to measure ripeness. The stiffness coefficient,  $f^2m$ , was derived from a formula for Young's modulus of elasticity by dropping all actual and assumed constants from the equation and minimizing computations. Density and Poisson's ratio were assumed to be constant within a fruit or vegetable species. This coefficient has been used by several subsequent investigators, although Cooke (1970) showed from theory that  $f^2m^{2/3}$  was more correct.

USDA Agricultural Marketing Service (AMS) interest in quantifying apple ripeness or condition prompted the examination of characteristics and methods inspectors presently use and the evalu-

ation of simple tests AMS inspectors could use. It also provided an opportunity to reexamine sonic vibrational characteristics for measuring texture in view of recent advances in electronic instruments and computers. A previous study (Abbott et al., 1992; Affeldt and Abbott, 1989) reports relationships among AMS ripeness scores, MT firmness measured manually, and sonic transmission characteristics for 'Delicious' apples that had been stored for  $\approx 3$  months. This paper reports the relationships among AMS ripeness scores, two destructive mechanical measurements, and sonic transmission characteristics for freshly harvested 'Delicious' apples. Primary objectives were to determine how well MT puncture force predicted inspectors' ripeness judgments and whether nondestructive sonic transmission tests could predict ripeness scores, MT values, or both.

## Materials and Methods

*Apples.* Commercial 'Delicious' apples of mixed, unspecified lots from the 1988 harvest were examined. The apples were selected during USDA inspections in the first week of Oct. 1988, so the apples had been held no more than 2 weeks under commercial handling conditions. Inspectors in Michigan, Minnesota, New York, Pennsylvania, and Washington each provided  $\approx 100$  apples including as broad a range of ripeness stages as possible. The apples were shipped by express mail ( $\approx 2$  days) to Beltsville, Md.

The apples were held for up to 1 week at 0C while all shipments were accumulated. Apples were numbered consecutively in the order of removal from the boxes. Apples from each state were separately randomized and then placed in trays of 20 apples to facilitate handling. Trays were henceforth tested in random order.

One box of apples at a time was removed from 0C, and the sonic transmission (described below), mass, and diameter between sonic contact points were recorded. The apples were returned to 0C. Apples were then removed two or three trays at a time to minimize temperature shifts. Apples were sequentially tested for MT, soluble solids concentration (SSC), inspectors' scores, and tissue compression. Apples were exposed to  $\approx 23$ C for 1 h at a time. Fruit temperature was not monitored and some warming undoubtedly occurred. It was assumed that the temperature shifts were small

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enough to cause negligible ripeness, firmness, or resonance changes. All measurements were completed within 5 days.

**Sonic measurements.** The Instrumentation and Sensing Laboratory (ISL) sonic transmission measurement was described by Abbott et al. (1992). Intact apples were mounted horizontally using floral clay to anchor them to an aluminum pedestal attached to an electromagnetic vibrator. An accelerometer was held firmly against the apple vertically opposite the vibrator. An electronic pulse (a sinc T pulse) containing all frequencies from 0 to 2000 Hz with equal energy density at each frequency was fed to a power amplifier to drive the vibrator. The vibrational response of the apple was detected by the accelerometer; signals from the accelerometer were collected by a signal analyzer. The frequency spectrum content (power spectrum) of the accelerometer signal was extracted by fast Fourier transformation with a resolution of 5 Hz. The signal analyzer averaged five responses from a single site. The average response curve (Fig. 1A) was obtained in <1 sec.

Amplitudes and frequencies of the second and third resonances ( $a_2$ ,  $a_3$ ,  $f_2$ , and  $f_3$ ) were extracted from the frequency response curves by computer and verified visually. Stiffness coefficients ( $f^2m$  and  $f^2m^{2/3}$ ) were calculated using  $f_2$  and  $f_3$ .

**MT firmness and soluble solids concentration.** An 11.1-mm MT probe (Ballauff Manufacturing Co., Laurel, Md.) was mounted in a universal testing machine (model TM; Instron Corp., Canton, Mass.) fitted with an optical encoder on the drive screw to track probe position. The testing machine and optical encoder were interfaced with a personal computer. Crosshead speed was 25.4 mm·min<sup>-1</sup>. MT firmness was measured at two opposite pored sites on the equator. The site for the first MT test was visually selected in the reddest area or opposite the greenest area, when such could be detected. The testing machine was programmed to detect contact with the specimen and then to travel 7.94 mm (5/16 inch) while collecting force data every 0.0254 mm. The force/deformation (F/D) curves (Fig. 1B) were recorded by computer and later analyzed for 30 force, slope, distance, and area data (Abbott et al., 1984). FFRC is force at fracture, rupture, or major tissue failure. FFUL is the force at full or maximum penetration. FMAX is the maximum force attained at any penetration. WORK is the area (energy) under the F/D curve to maximum penetration. M@0.5 is the slope at 0.5 mm penetration.

The juice expressed during MT penetration was collected, and SSC was determined using a hand refractometer.

**Ripeness assessment.** The 20 apples from one tray were arrayed under fluorescent lights for inspection. The USDA inspector whose data best correlated with the mean of five other inspectors in a related study (Abbott et al., 1992) was selected to make all ripeness judgments in the present study. A second, less experienced inspector, who had not participated in the previous study, separately scored the apples after the primary judge. Their data are designated AMS1 and AMS2, respectively. Inspectors were given no instructions as to how to evaluate ripeness except to do it as they normally did in inspection. They were permitted to bruise, cut, and taste the fruit as much as needed. They were only required to leave sufficient intact area for the compression test specimen to be taken (described below).

The inspectors used verbal scores that were converted to numeric scores by an observer who entered them into the computer. The basic AMS ripeness categories were coded as 0 = severely overripe or too damaged to evaluate, 1 = overripe, 2 = ripe, 3 = firm ripe, 4 = firm, and 5 = hard. Note that increasing values indicate increasing firmness and, conversely, decreasing ripeness. No apples were judged immature. The inspectors were allowed to fragment the AMS ripeness categories. Fragmented categories

were coded by either adding or subtracting 0.3 point for a judgment of upper or lower end of the category. For example, upper firm ripe would be approaching firm and would be entered as 3.3. Data were also converted to the traditional five categories for analysis. Any apple given a 0 score by either inspector was eliminated.

**Compression tests.** Compression tests were made on the universal testing machine (Abbott et al., 1982, 1984). A radial cylinder

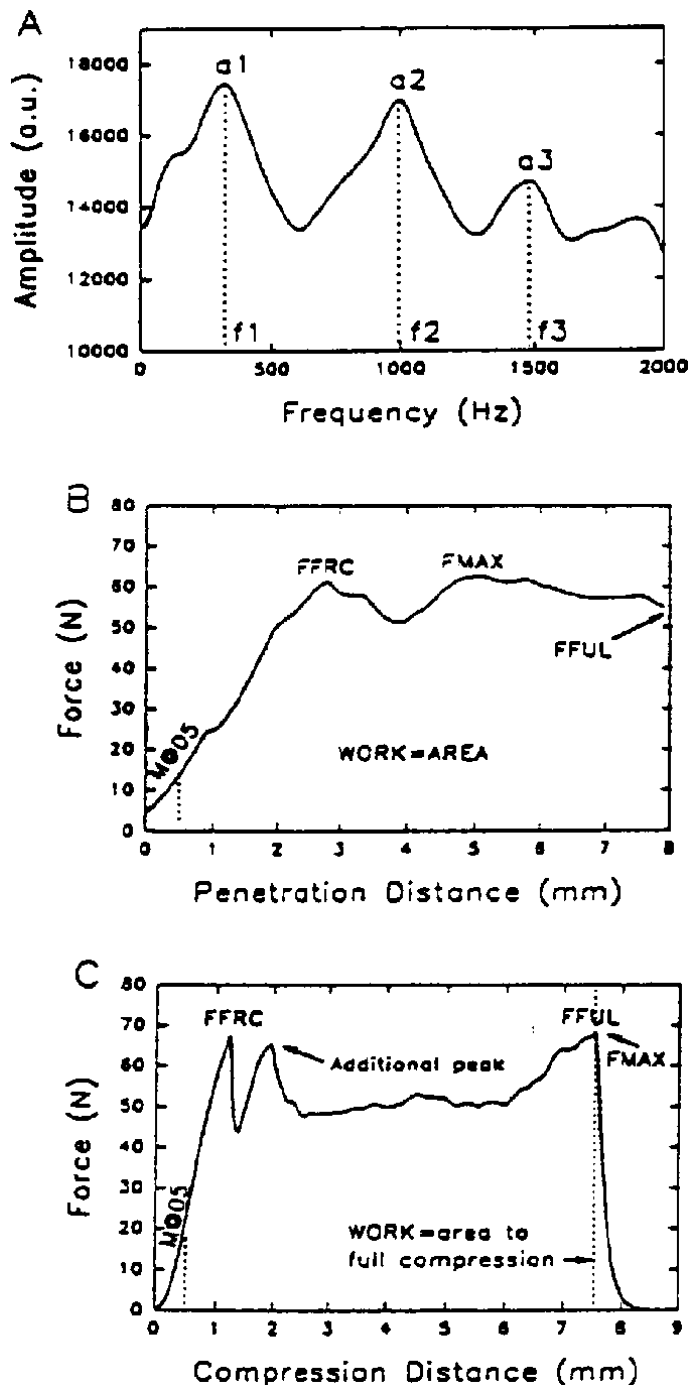


Fig. 1. Typical curves for 'Delicious' apples measured by (A) Instrumentation and Sensing Laboratory's sonic transmission, (B) Magness-Taylor, and (C) tissue compression. (A)  $a_1$ ,  $a_2$ ,  $a_3$ ,  $f_1$ ,  $f_2$ , and  $f_3$  are amplitudes (a) and frequencies (f) of resonant modes 1, 2, and 3, respectively. (B and C) FFRC is fracture or rupture force; FFUL is force at maximum penetration or compression; WORK is area under curve to FFUL; and FMAX is maximum force and may occur at FFRC, FFUL, or at occasional additional peaks that occur between FFRC and FFUL, especially in crisp, firm apples. M@05 is the slope at 0.5 mm penetration or compression.

of apple flesh was removed from the equator using a 15-mm-diameter corkborer. A 2.5-mm slice of the cylinder including the skin was discarded and the next 10-mm segment was tested in compression between flat plates at 25.4 mm·min<sup>-1</sup>. The testing machine was programmed to detect contact with the specimen, travel 7.5 mm, reverse, and continue to collect data for 2.5 mm. The F/D curves (Fig. 1C) were recorded by computer, and data comparable to those for MT were later extracted.

**Statistical analyses.** The experimental design was completely random, with unequal numbers of apples from the five sources. Grouping on trays was ignored. Seventy two apples were rejected because they had physiological breakdown, received ripeness scores of 0, were dropped during testing, or were missing a measurement. Analyses reported are based on 406 apples.

Ripeness categories were created by grouping all apple records with the same AMS1 score, resulting in 13 categories with 1 to 54 apples in each. MT classes were generated by converting MTFMAX to pounds-force (the traditional MT units) rounded to the nearest integer value, resulting in 14 classes with one to 61 apples. Data for apples within categories or classes were averaged. It is important to note that each ripeness category mean or MT class mean represents a different number of apples.

The amplitude at the best fixed frequency in the ISL sonic measurement was found by performing regressions of ripeness,

MT, or compression values on sonic amplitudes at each successive frequency and selecting the highest correlation coefficient.

## Results and Discussion

There was a wide distribution of apples over the range of ripeness categories (Table 1). Variability within ripeness categories, indicated by coefficients of variation, increased with increasing ripeness for most variables measured. Firmness measured by MTFMAX ranged from 27.7 to 96.0 N and averaged 59.8 ± 12.3 N over all 812 MT punctures.

The ripeness scores of the second inspector generally agreed with those of the primary inspector ( $r = 0.80$ ), but were slightly more variable when compared with MT values. Although correlations with other measurements were improved by using the mean of the two inspectors, only  $r$  values based on individual inspectors are reported because, in practice, ripeness scores are determined by a single inspector.

SSC was poorly correlated with either inspector's ripeness scores ( $r \leq -0.39$ ), mass ( $r = 0.24$ ), MTFMAX ( $r = 0.22$ ), or sonic resonant frequencies ( $r \leq -0.27$ ). SSC did not contribute significantly to prediction of ripeness scores in multiple regression analyses with MT or compression data.

The MT<sub>b</sub>FMAX from the first (blush) side averaged only 0.7 N

Table 1. Means of selected measurements<sup>2</sup> for apples within ripeness categories, i.e., apples given the same ripeness score by the Agricultural Marketing Service (AMS) primary inspector, AMS1.

Ripeness category	n	AMS1		AMS2		MTFMAX		TCFMAX		f <sub>2</sub>		f <sub>3</sub>		f <sub>3</sub> <sup>2</sup> m		f <sub>3</sub> <sup>2</sup> m <sup>2/3</sup>	
		$\bar{x}$	CV (%)	$\bar{x}$	CV (%)	$\bar{x}$ (N)	CV (%)	$\bar{x}$ (N)	CV (%)	$\bar{x}$ (Hz)	CV (%)	$\bar{x}$ (Hz)	CV (%)	$\bar{x}$	CV (%)	$\bar{x}$	CV (%)
Hard	45	5.0	1	4.1	16	73	7	93	12	504	9	1158	8	212	9	39.1	7
Firm	122	4.0	6	3.6	19	69	10	82	21	497	10	1141	9	199	10	37.1	9
Firm ripe	129	3.0	9	2.8	21	58	10	60	21	471	10	1055	8	189	13	34.1	12
Ripe	93	2.0	12	2.1	33	48	14	49	25	447	11	1023	8	173	15	31.6	14
Overripe	17	1.0	10	1.1	31	37	15	36	15	397	16	929	10	147	18	26.6	18

<sup>2</sup>AMS1 and AMS2 = ripeness scores of AMS inspectors 1 and 2; MTFMAX = Magness-Taylor maximum force, mean of two sides; TCFMAX = tissue compression maximum force; f<sub>2</sub> and f<sub>3</sub> = frequencies at sonic resonance modes 2 and 3; f<sub>3</sub><sup>2</sup>m and f<sub>3</sub><sup>2</sup>m<sup>2/3</sup> = stiffness coefficients, shown ×10<sup>-6</sup>.

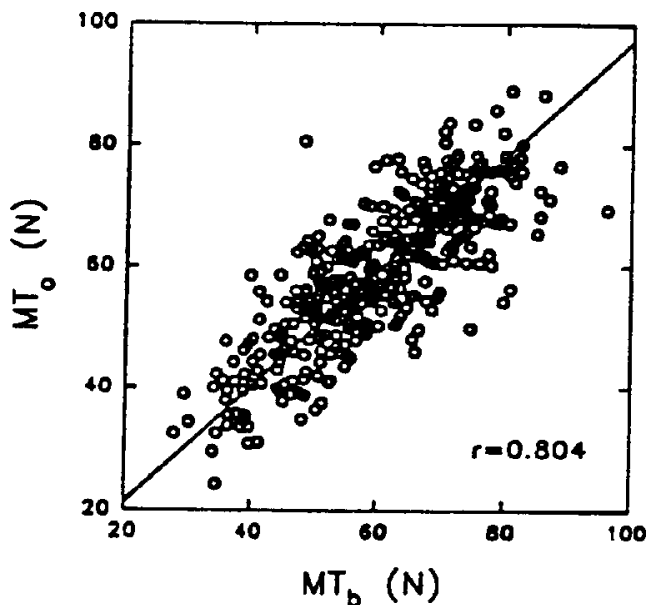


Fig. 2. Variation in Magness-Taylor maximum forces between opposite sides of 'Delicious' apples. MT<sub>b</sub> and MT<sub>o</sub> are maximum force on blush and opposite sides, respectively.

Table 2. Relationships among selected measurements for 406 apples (correlation coefficients,  $r$ ).

Measurement <sup>2</sup>	AMS1	MTFMAX	f <sub>2</sub>	f <sub>3</sub>	Stiffness coefficients	
					f <sub>3</sub> <sup>2</sup> m	f <sub>3</sub> <sup>2</sup> m <sup>2/3</sup>
MTFMAX	0.844	---	0.517	0.587	0.465	0.597
MTFFUL	0.849	0.964	0.538	0.605	0.499	0.629
MTWORK	0.852	0.987	0.555	0.618	0.517	0.647
TCFMAX	0.787	0.869	0.383	0.509	0.323	0.463
TCFFUL	0.778	0.852	0.363	0.507	0.303	0.449
TCWORK	0.838	0.894	0.406	0.522	0.402	0.525
AMS1	---	0.844	0.475	0.567	0.546	0.645
Mass	-0.173	-0.244	-0.398	-0.708	0.274	-0.152
Diameter	-0.185	-0.284	-0.362	-0.630	0.247	-0.134
Density	0.084	0.167	0.105	0.146	-0.048	0.042

<sup>2</sup>MTFMAX = Magness-Taylor (MT) maximum force, mean of two sides; MTFFUL = MT force at maximum penetration; MTWORK = MT area (energy) under the F/D curve to maximum penetration; TCFMAX = tissue compression (TC) maximum force; TCFFUL = TC force at full compression (75%); TCWORK = TC area (energy) under the F/D curve to full compression; f<sub>2</sub> and f<sub>3</sub> = frequencies at sonic resonance modes 2 and 3; m in stiffness coefficients = mass. Density was approximated as mass/[4/3π (diam/2)<sup>3</sup>].

firmer than MT<sub>0</sub>FMAX from the opposite side, although some individual apples varied much more (Fig. 2). The correlation coefficient between MTFMAX for opposite sides of each apple was 0.80. Therefore, the best correlation we can realistically expect to achieve between MT firmness and any other measurement will be of similar magnitude. Means of the MT data from both sides are used for all further analyses.

MT is generally accepted as the standard firmness measurement in the apple industry. MTFMAX, the value normally obtained in manual MT tests, correlated well with AMS1 (Table 2) and AMS2. However, there was a wide range of MTFMAX values within each AMS1 category, and Fig. 3 shows that an apple with a specific MTFMAX value may fall in several AMS categories; for example, an apple measuring 60 N could fall within AMS categories 2 through 5. Compression test data generally did not correlate quite as highly with inspectors' scores or with sonic data as comparable MT data (Tables 2 and 3). Interestingly, in most comparisons with either MT or compression, WORK gave very slightly higher *r* values than FMAX. With electronic instruments, the area under the F/D curve is about as easy to obtain as maximum force. It may be desirable in future fruit firmness studies to obtain FMAX and WORK to evaluate the usefulness of WORK.

The conspicuous features of the sonic transmission spectra are the amplitudes and frequencies of the peaks (Fig. 1A). The first, rather noisy, sonic resonant peak was identified as resulting from the combination of equipment and apple and was not considered further. Amplitudes at each successive frequency ( $A_5$  to  $A_{2000}$ ) and the amplitudes and frequencies of the second and third resonance peaks ( $a_2$ ,  $a_3$ ,  $f_2$ , and  $f_3$ ) were correlated singly and in combinations with the inspectors' scores, MT, and compression data. Correlations of MT or inspector's scores with amplitudes at specified sonic frequencies or at resonances were never as high as correlations with resonant frequencies. For example, correlation between MTFMAX and amplitude at the best fixed frequency was  $r = 0.31$  and between MTFMAX and  $a_2$  or  $a_3$  was  $r \leq 0.13$ , while the correlation between MTFMAX and  $f_3$  was  $r = 0.59$ . Amplitudes

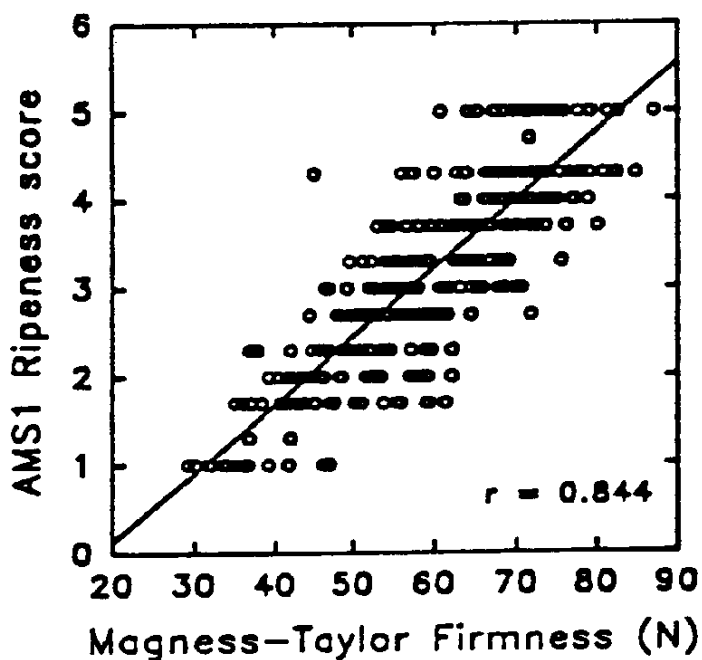


Fig. 3. Relationship between the Agricultural Marketing Service (AMS) primary inspector's ripeness scores (AMS1) and Magness-Taylor firmness (mean of maximum forces for two sides) for 406 'Delicious' apples.

depend on solidness of apple-to-vibrator and apple-to-detector contacts and flesh characteristics. Resonant frequencies primarily depend on elastic properties and dimensions of the apple. Thus, only the resonant frequencies are included in further analyses.

Correlations of inspectors' scores, MT, or compression data with the resonant frequencies of the third peak were higher than those with resonant frequencies of the second peak (Table 2). Similarly, relationships with stiffness coefficients based on  $f_3$  were higher than those based on  $f_2$ ; therefore, stiffness coefficients derived from  $f_2$  are not shown. It is worth noting that  $f_3$  depended more than  $f_2$  on fruit size (mass and diameter); that may or not be a consideration in application.

From theory (Cooke, 1970) and in our previous studies, mass correlated highly negatively with resonant frequencies. That was partially true for this set of apples. Mass and diameter had a greater influence on  $f_3$  than on  $f_2$  (Table 2). Mass was selected as a significant variable after resonant frequency in stepwise multiple regressions with MT or compression data as the dependent variable. Diameter was not as closely related to resonant frequencies as mass. Correlation between mass and diameter was only  $r = 0.89$  and between mass and calculated spherical volume was  $r = 0.88$ . Although size was not highly correlated with MT and compression data, diameter had slightly more effect than mass on MT and compression forces (Table 2). According to theory, density is related to resonant frequencies. Density was not measured directly, but apparent density was calculated from mass and diameter. Including apparent density in multiple regression models did not improve correlation coefficients.

The ability of sonic resonant frequencies and stiffness coefficients to predict inspectors' scores and MT values for individual apples was tested (Table 2, Fig. 4 A-D). Using the stiffness coefficient improved the apparent relationship of sonics to ripeness scores, especially at the higher and lower AMS1 values (Fig. 4 B vs. A), even though the correlation coefficient was not improved. Similarly, the relationship between sonics and MT appears somewhat sigmoidal in Fig. 4C; using the stiffness coefficient tends to linearize the relationship. The  $f_2^2m$  and  $f_2^2m^{2/3}$  were the poorest predictors of inspectors' scores, followed sequentially by  $f_2$ ,  $f_3^2m$ , and  $f_3$ . Inspectors' scores were best predicted by the stiffness coefficient  $f_3^2m^{2/3}$ .

Table 3. Relationships among selected measurements for ripeness categories based on scores of Agricultural Marketing Service (AMS) primary inspector, AMS1 (correlation coefficients, *r*, for  $n = 13$  category means, with 1 to 54 apples per mean).

Measurement <sup>2</sup>	AMS1	$f_2$	$f_3$	Stiffness coefficients	
				$f_3^2m$	$f_3^2m^{2/3}$
MTFMAX	0.988	0.914	0.968	0.937	0.959
MTFFUL	0.990	0.928	0.973	0.938	0.963
MTWORK	0.989	0.929	0.975	0.948	0.969
TCFMAX	0.982	0.891	0.957	0.900	0.934
TCFFUL	0.981	0.890	0.954	0.897	0.932
TCWORK	0.986	0.887	0.958	0.906	0.938
AMS1	---	0.925	0.967	0.958	0.973

<sup>2</sup>MTFMAX = Magness-Taylor (MT) maximum force, mean of two sides; MTFFUL = MT force at maximum penetration; MTWORK = MT area (energy) under the F/D curve to maximum penetration; TCFMAX = tissue compression (TC) maximum force; TCFFUL = TC force at full compression (75%); TCWORK = TC area (energy) under the F/D curve to full compression;  $f_2$  and  $f_3$  = frequencies at sonic resonance modes 2 and 3;  $m$  in stiffness coefficients = mass.

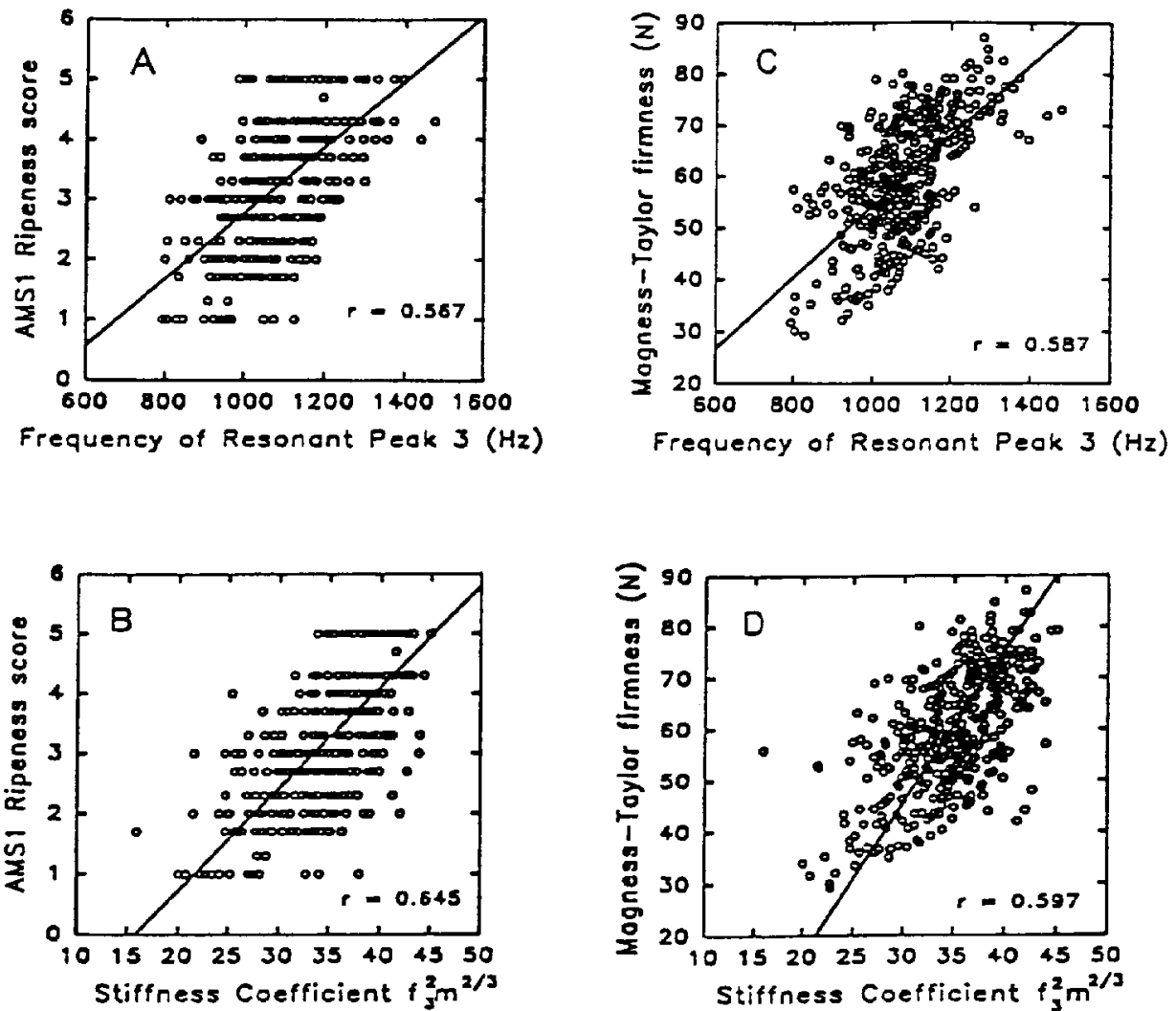


Fig. 4. Relationships between Agricultural Marketing Service (AMS) primary inspector's ripeness scores (AMS1) or Magness-Taylor firmness (MTFMAX) and sonic transmission characteristics for 'Delicious' apples ( $n = 406$ ). (A and B) Ripeness scores vs. frequency of resonant peak 3 ( $f_3$ ) or stiffness coefficient calculated from that frequency and mass ( $f_3^2 \times m^{2/3}$ ). (C and D) Mean Magness-Taylor firmness vs. frequency of resonant mode 3 or stiffness coefficient.

Although the correlation coefficients are not high enough to predict the exact values for individual apples, it is obvious that the sonic resonant frequency was closely related to ripeness score and MT firmness. When all apples with a given AMS1 ripeness score were averaged and the data were compared, the correlations were very high (Table 3, Fig. 5). Similarly, when all apples with the same nominal MT firmness value were averaged, correlations between sonic data and inspectors' scores or instrument tests were also very high (Table 4).

### Conclusions

SSC was not significantly correlated to any other measurement in this study. MT maximum force or work predicted the ripeness scores of apple inspectors better than compression test data or sonics. Human inspectors are quite variable and, despite being more objective, MT puncture tests are recognized as being relatively variable. Despite the variability of those destructive methods, sonic transmission data were correlated to both when averages of groups of apples were compared, and sonics has the advantage of being nondestructive. Of the sonic transmission data examined, frequency of the third resonance mode or the more theoretically

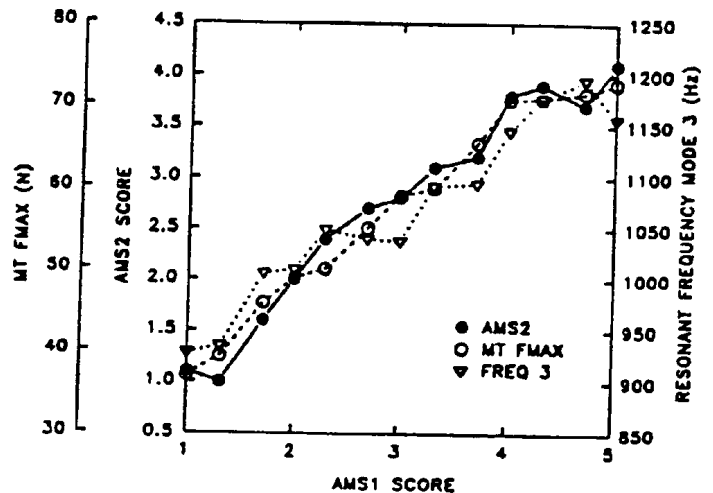


Fig. 5. Overview of relationships of the Agricultural Marketing Service (AMS) primary inspector's ripeness scores (AMS1) to Magness-Taylor firmness (MTFMAX), the other inspector's ripeness scores (AMS2), and frequency of resonant peak 3 ( $f_3$ ). Each point represents the mean of all apples with the same AMS1 score and may represent from 1 to 54 apples.

Table 4. Relationships among selected measurements<sup>2</sup> for firmness classes based on mean MTFMAX values (correlation coefficients, *r*, for *n* = 14 MT class means, with 1 to 61 apples per mean).

Measurement	AMS1 <sup>y</sup>	f <sub>2</sub>	f <sub>3</sub>	Stiffness coefficients	
				f <sub>3</sub> <sup>2</sup> m	f <sub>3</sub> <sup>2</sup> m <sup>2/3</sup>
MTFMAX	0.994	0.959	0.957	0.904	0.959
MTFFUL	0.988	0.956	0.962	0.886	0.953
MTWORK	0.995	0.963	0.954	0.916	0.964
TCFMAX	0.979	0.928	0.946	0.844	0.923
TCFFUL	0.975	0.922	0.943	0.832	0.915
TCWORK	0.987	0.931	0.941	0.857	0.928
AMS1	---	0.952	0.939	0.917	0.956

<sup>2</sup>MTFMAX = Magness-Taylor (MT) maximum force, mean of two sides; MTFFUL = MT force at maximum penetration; MTWORK = MT area (energy) under the F/D curve to maximum penetration; TCFMAX = tissue compression (TC) maximum force; TCFFUL = TC force at full compression (75%); TCWORK = TC area (energy) under the F/D curve to full compression; f<sub>2</sub> and f<sub>3</sub> = frequencies at sonic resonance modes 2 and 3; m in stiffness coefficients = mass; AMS1 = Agricultural Marketing Service primary inspector's ripeness score.

correct stiffness coefficient based on that frequency (f<sub>2</sub>m<sup>2/3</sup>) gave the best model for either MT or ripeness scores.

The results of the sonics test are promising, but further research is needed to refine the sonic method to improve the prediction of the firmness of individual apples and make the test simpler and faster. Currently, the prediction of MT firmness values or inspectors' ripeness scores for individual apples is poor. However, it is at least as good as that obtained by other nondestructive methods published to date. Multiple-site sonic tests or different mathematical treatment of the data may improve firmness prediction.

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