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NON-DESTRUCTIVE METHOD FOR MEASUREMENT OF MELON FIRMNESS DURING STORAGE AND SHELF-LIFE

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A b s t r a c t. In many fruits, and melons in particular, it is desired to replace destructive firmness measurement methods, by non-destructive ones. A new non-destructive method for evaluating melon firmness and shelf-life is presented by a study on two melon samples of the Galia cultivar, one with sparsely netted skin and the other with relatively densely netted skin. The line taken assesses the performance of the non-destructive fruit firmness sensor, which is based on vibrational excitation, versus the conventional destructive test which measures the applied piercing force on the inspected fruit by a penetrometer. The distribution of the differences between the readings of the two methods, after suitable translation of the non-destructive readings to the piercing force scale in Newtons, shows about 12-15 % difference of full scale, in about 70% of the population. A comparison is also made to sensory hand squeezing judgments of expert inspectors. An independent measure for assessing the sensitivity of the non-destructive sensor to melon aging, is presented by taking time spaced firmness readings on a fruit sample, at the same locations of each fruit. The superior sensitivity of the non-destructive method to melon ageing, renders it particularly suitable for sorting melons by predicted shelf-life. Freshly harvested melons, that show higher readings will generally have a longer shelf-life.

K e y w o r d s: *Cucumis melo* cv *Reticulatus*, firmness, vibration excitation, storage life, shelf-life

INTRODUCTION

A precise definition of fruit firmness in general and melon firmness in particular is probably impossible because the textural property 'firmness' is a conglomerate of various physical and geometrical properties of the fruit. Nevertheless, there is usually no difficulty in assessing the firmness of fruits subjectively, by simply eating them. The human mouth is very sensitive to texture variations so we can immediately tell a soft melon from a firm one. Thus, although we know intuitively what 'firmness' is, we will probably never be able to measure it precisely with our crude instruments.

Traditionally, firmness measurements of fruits and vegetables and melons in particular, are predominantly destructive, using pressure testers that measure the force required to penetrate to a given depth into the fruit flesh [1-5]. Inspectors sometimes employ subjective sensory assessment of melon firmness by hand squeezing.

In many fruit types it is desired to replace the destructive method or manual sensory measurement methods by non-destructive means, whereby the firmness of the same fruits can be measured repeatedly over the time span of its storage and shelf-life. The objective of the present article is to report some results of non-destructively measuring melon firmness, which may also be used for shelf-life prediction, by a new fruit firmness sensor described in detail in [6-8].

MATERIALS AND METHODS

The non-destructive fruit firmness sensing system is depicted in Fig. 1. It comprises an electrodynamic shaker, for vibrationally exciting the bottom part of the inspected fruit, using an optimized frequency profile and input RMS (root mean square) acceleration level $\ddot{X}_i$, specialized for each fruit type. The output RMS acceleration $\ddot{X}_o$ is measured by a transducer attached to a sensor finger contacting the top part of the fruit, whereby a firmness index *PFT* (Peleg Firmness Test) is derived by:

$$PFT = \ddot{X}_o/(\ddot{X}_o - \ddot{X}_i) \qquad (1)$$

Softer fruits transmit a smaller fraction of the input vibration energy than firm fruits, thus larger values of *PFT* correspond to relatively firmer fruits. From Eq. (1) it is clear that the *PFT* readings are non dimensional ratios. This renders them insensitive to fruit size and variations in the magnitude of the input acceleration level $\ddot{X}_i$. Because the effect of the fruit mass is similar on the input and output accelerations, the *PFT* ratio remains approximately unaffected by the mass variations when measuring firmness of a given fruit variety, i.e., large and small tomatoes, or large and small melons.

In operation the user raises the sensor finger with one hand while positioning the fruit onto the vibrator head with the other hand. The sensor finger is then lowered onto the fruit whence the input and output acceleration signals are automatically acquired by a microcomputer and a *PFT* reading is computed. This sensor was extensively tested on firmness measurements of apples [7], avocado [9] and tomatoes [8]. Herein, we similarly report on its possible application for measuring firmness of melons.

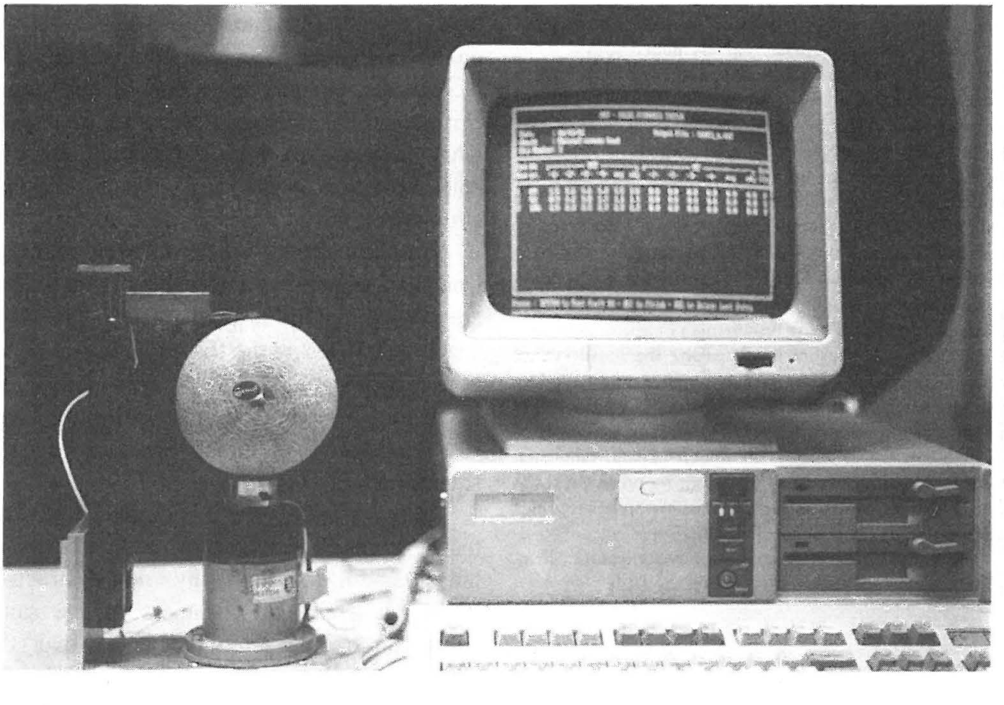

Fig. 1. Non-destructive fruit firmness measurement system, showing sensor and microcomputer. In operation, one side of the fruit is placed on the head of the vibrator and the sensor finger is lowered onto its other side, as shown. A firmness reading is then automatically recorded by the microcomputer.

The firmness of melons was measured by the non-destructive sensor, as well as by the piercing force of a conventional destructive penetrometer tool. A 6 mm diameter cone shaped tip of a commercial pressure tester (John Chatillon and Sons Inc., 83-30 Kew Garden N.Y., N.Y) was used to obtain the piercing force in N (Newtons). The melons tested were of the Galia cultivar harvested from a field in the Arava region in Israel. We selected two representative Galia melon samples; one with a sparsely netted skin (SN) and the other with relatively densely netted skin (DN).

In these experiments, the *PFT* and Chatillon (*CT*) readings were taken at the same locations on each melon. Four measurements per melon were taken, about 90 degrees apart, around the circumference of the fruit, wherein the average value of these four measurements were taken as *PFT* and *CT* firmness indexes of the fruit. The firmness indexes thus obtained, in the two melon samples are summarized in Table 1.

The data of Table 1 reveals the inherent unreliability of the *CT* firmness index. Observe first that CT_{av} and CT_{max} in the second melon sample were almost twice as large as in the first. This is because the *CT* readings are predominantly influenced by the resistance of the skin to piercing by the penetrometer tip, while the stiffness of the fruit flesh is of secondary importance. In contrast, the *PFT* readings were approximately in the same range, in both samples.

To overcome this problem, we tried to remove the skin of the melon at the measurement locations, before taking the *CT* readings, as is the practice in measuring firmness of apples [4]. This procedure was unsuccessful because the relatively soft fleshy mesocarp of both 'soft' and 'firm' Galia melons showed essentially the same low *CT* readings.

Furthermore, the flesh of the melons is not uniform, it becomes softer and softer as the plunger penetrates deeper, i.e., further from the 'peel'. Consequently, the penetrometer reading is very dependent on the thickness of the removed part, which is difficult to standardize because there is no way to tell where exactly the 'peel' ends and were the 'flesh' begins. Anyway, from our experience, the most meaningful results are obtained when the firmness of the whole melon is considered, especially for shelf-life prediction.

Table 1. Summary of data from two melon samples

Test	No.	CT_{max}	CT_{min}	CT_{av}	STD_{ct}	PFT_{max}	PFT_{min}	PFT_{av}	STD_{pft}	R
SN skin	64	48.0	6.3	23.4	8.9	7.9	0.8	2.9	1.6	0.76
DN skin	60	86.8	11.0	39.5	17.4	9.1	0.5	3.0	2.4	0.70

The headings of the columns in Table 1 have the following meanings: No. - the number of fruits in each sample; CT_{max}, CT_{min}, - the maximal and minimal piercing forces, in Newtons. CT_{av} and STD_{ct} - the averages and standard deviations of these readings. PFT_{max}, PFT_{min}, PFT_{av} and STD_{pft} - the respective values of the readings by the non-destructive method; R - is the correlation coefficient between the *CT* and *PFT* readings.

Each of the two fruit samples was divided into two equal groups. The first group of 32 melons of sample 1 were tested about 2 days after harvest, while the remaining 32 melons were tested 10 days after harvest. Similarly, the first group of 30 melons of the second sample were tested about 6 days after harvest, while the second group was tested 13 days after harvest. To obtain a wide range of firmness quickly, the melons were stored at 20 °C and 85-90 % relative humidity, wherein the first groups were labelled 'firm' while the second groups were designated as a 'soft' category.

Thus, removing the skin renders the *CT* readings essentially insensitive to melon ageing, but if the skin is not removed the *CT* readings are biased by the thickness of the skin. As the latter case is the lesser of the two evils, we decided to take the *CT* readings through the skin of the melon.

Commercial quality inspection of melons in Israel is based on sensory hand squeezing by expert inspectors, who classify melons into two categories: 'firm' and 'soft'. An extensive study was conducted at a commercial inspection station, wherein the *PFT* readings were compared to the judgments of the inspectors.

RESULTS

A plot of *CT* versus *PFT* readings of fruit sample 1 in Table 1, is shown in Fig. 2. The 32 'firm', less aged melons are marked by 'o' while the 32 'soft' melons that were aged 8 days more are marked by 'x'. The correlation coefficient between the *CT* and *PFT* readings was R=0.76, which is quite good. Note however, that R is a poor indicator, for comparing firmness measurement methods, because it is strongly dependent on the firmness range in the inspected sample. Thus, if the 'soft' category is considered separately, the correlation coefficient would be R=0.48, and similarly in the 'firm' category alone R=0.49.

A better way of comparison between the two firmness measurement methods, which is less dependent on the range of the firmness in the inspected sample, is to translate the *PFT* readings to the *CT* scale, by the equation of the optimal scale translation line, as depicted in Fig. 2a:

$$PFT_{ct} = 4.7704\,PFT + 9.3932 \qquad (2)$$

where PFT_{ct} are the best estimates of the *CT* readings in Newtons, given the measured *PFT* values. Clearly, the differences $D=(PFT_{ct} - CT)$ indicate the disagreements between the two firmness measurement methods. That is, the two methods should give identical results if D=0 for all the fruits in the inspected sample, while the scatter of D indicates the inherent difference between the two methods.

It is useful to plot the scatter of D versus the mean values $M = (PFT_{ct} + CT)/2$, as depicted in Fig. 2b, for fruit sample 1 in Table 1. Since we do not know which one of the two methods measures 'true firmness', M is a logical

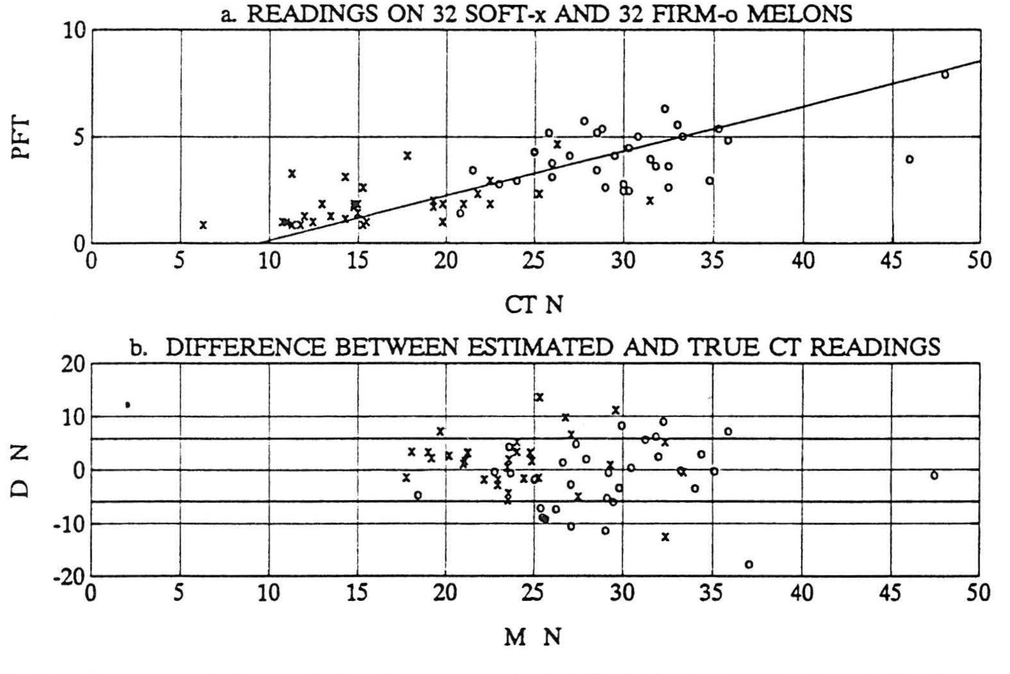

Fig. 2. (**a**) Scattergram of *CT* versus *PFT* readings on a sample of 64 'firm' (o) and 'soft' (x) melons. (**b**) Distributions of differences between estimated and true *CT* readings on the melon sample of Fig. 2a after translation from *PFT* to PFT_{ct} by the scale translation line represented by Eq. (2).

compromise. Assuming that the scatter of the differences between the readings by the two methods is normally distributed, about 70 % of their population should fall within ± one standard deviation *SD* of *D*. In the example of fruit sample 1, SD=5.9 N, as depicted by the two horizontal lines in Fig. 2b. The full range of the *CT* readings in this sample was about CT_{max}=48 N, so 5.9 N is about 12 % of full scale. Indeed, by visual inspection of Fig. 2b one observes that most of the readings fall between the two horizontal lines of $\pm SD$=5.9 N.

Similar calculations for fruit sample 2 in Table 1 yields $\pm SD$=12.9 N, which is about 15 % of full scale, given that CT_{max}=86.8 N. As expected, the difference between the *CT* and *PFT* readings is larger in the thick skinned densely netted melon sample.

The destructive method of measuring fruit firmness by the pressure tester method has been around for many years, so it has become a generally accepted standard. However, it is not necessarily better than the non-destructive *PFT* method, especially in light of the main purpose for measuring fruit firmness, which is shelf-life prediction. It is well known that firm ripe melons have a longer shelf-life than soft melons. Thus, an independent assessment of the *PFT* and *CT* methods may be obtained, by their ability to detect ageing differences in melons, as depicted in Figs 3a and 3b, for fruit sample 2 in Table 1. The readings on the 30 'firm' melons marked by o's are plotted together with the readings on the 30 soft melons, marked by x's.

The horizontal lines mark the optimal thresholds that can sort the melons into 'soft' and 'firm' categories, with minimal missclassifications. The number of crossings of x's and o's above and below these threshold lines respectively, express the resulting soft in firm (SinF) and firm in soft (FinS) misclassifications. A firmness sensitivity index (*FSI*) may be defined by:

$$FSI = 100\,\frac{\text{SinF} + \text{FinS}}{\text{No.}}\,\% \qquad (3)$$

where No. denotes the number of fruits in the inspected sample. Smaller *FSI* values indicate less misclassifications and hence better separation between the 'soft' and 'firm' categories, i.e., better sensitivity to firmness reduction with time.

The Mean Dynamic Range (*MDR*) is another way of expressing this property:

$$MDR = \frac{\begin{array}{c}\text{Mean of firmness readings}\\ \text{in the 'firm' fruits sample}\end{array}}{\begin{array}{c}\text{Mean of firmness readings}\\ \text{in the 'soft' fruits sample}\end{array}} \qquad (4)$$

Here, larger *MDR* values indicate better separation between the 'soft' and 'firm' categories, i.e., better sensitivity to firmness reduction with time. Table 2 compares the *FSI* and *MDR* values by the *CT* and *PFT* methods, for the SN and DN melon samples in Table 1.

The figures in Table 2 indicate that in the thinner skinned SN melons the sensitivities to firmness reduction with time of the *CT* and *PFT* methods are quite similar, with a slight advantage to the *CT* method. But, in the thicker skinned DN melons the *PFT* method was about twice more sensitive than the *CT* to firmness reduction.

The superior sensitivity of the non-destructive *PFT* method to melon ageing, renders it particularly suitable for sorting melons by predicted shelf-life. Freshly harvested melons, that show higher *PFT* readings will generally have a longer shelf-life, as demonstrated in Fig. 4. In this test, a sample of 25 melons of various initial *PFT* firmness readings, were

Table 2. Indicators of firmness reduction with time

Test	No.	FSI_{CT} %	MDR_{CT}	FSI_{PFT} %	MDR_{PFT}
SN skin	64	7.8	3.3	10.9	3.2
DN skin	60	21.7	1.7	11.7	3.2

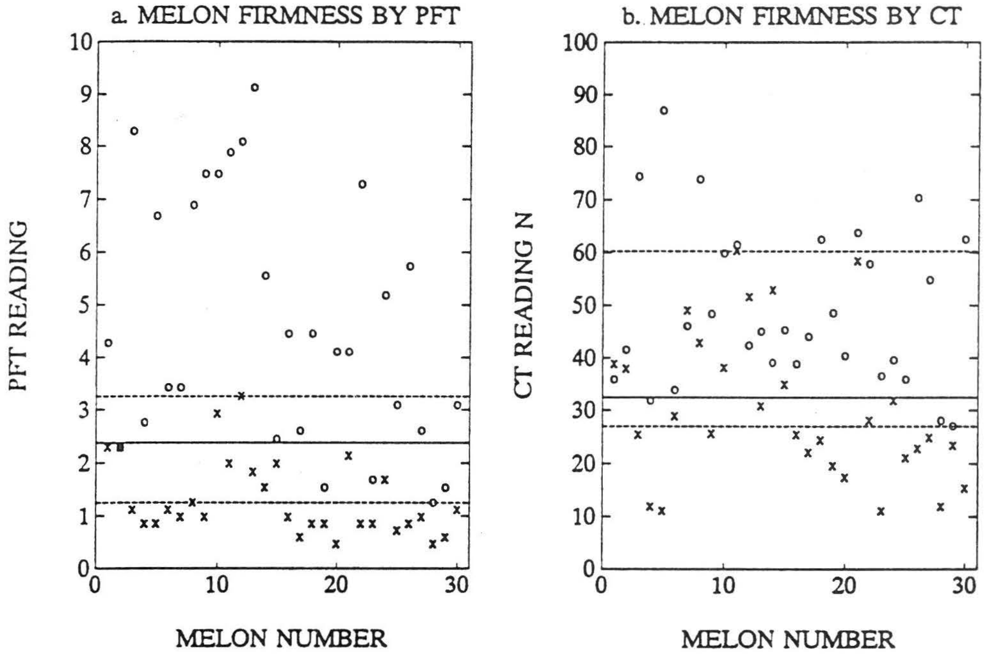

Fig. 3. Scattergrams of *PFT* readings (**a**) and *CT* readings (**b**), on a sample of 30 'soft' (x) melons and 30 'firm' (o) melons.

stored at room temperature, while taking consecutive *PFT* readings at the same locations on each fruit, every two days. In Fig. 4, the horizontal line of *PFT*=2.5 was chosen arbitrary, as a cut off firmness level which indicates the end of the useful shelf-life of these melons. In practice, this cut off *PFT* level may be varied by experience, depending on the melon variety. When the *PFT* value of a melon dropped below 2.5, it was discarded, while its *PFT* value for the next reading was set to *PFT*=0, indicating the end of its useful shelf-life.

From Fig. 4, it may be seen, that by and large, the shelf-life of firmer melons is longer, as might be expected. The useful shelf-life of melons with initial *PFT* values of 5 and less (marked by dashed lines) was about 4 days, while the shelf-life of melons that showed initial *PFT* readings over 5, (as marked by the solid lines) was up to 13 days. Exceptions may occur of course, as demonstrated by the dashed line of a relatively soft melon with initial *PFT*≈5, which had a shelf-life of 7 days, while the useful shelf-life of the relatively firm melon with an initial *PFT*=6 was only 5 days.

The plot in Fig. 5 is a typical example of results obtained at a commercial quality inspection station, where Galia melons are inspected after a simulated transport and storage regime of 4 days at 5 °C followed by 5 days at room temperature, e.g., 20-25 °C. In conjunction with other quality attributes, expert inspectors classify these melons into 'firm' and 'soft' categories by sensory hand squeezing. In this example, the *PFT* readings on a randomly selected sample of 75 melons are plotted, while those classified as 'firm' and 'soft' by the experts are marked by o's and x's respectively.

It may be seen that by and large there is a good agreement between the *PFT* readings and the judgments of the inspectors. Note that a brake *PFT* value of 2.5 marked by the horizontal line separates between the 'firm' and the 'soft' melons quite well.

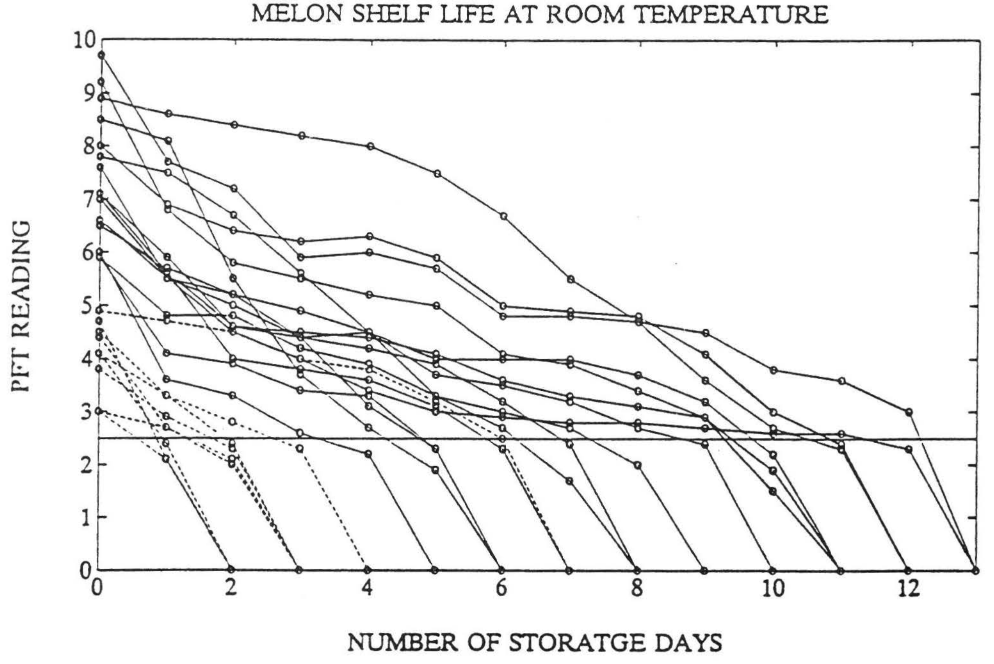

Fig. 4. Reduction of melon firmness with time, as indicated by consecutive *PFT* measurements every two days, on a sample of 25 melons stored at room temperature. The horizontal line of *PFT*=2.5 was chosen arbitrary, as a cut off firmness level which indicates the end of the useful shelf-life of these melons. The thick solid line denotes the mean firmness reduction of the entire melon sample with time.

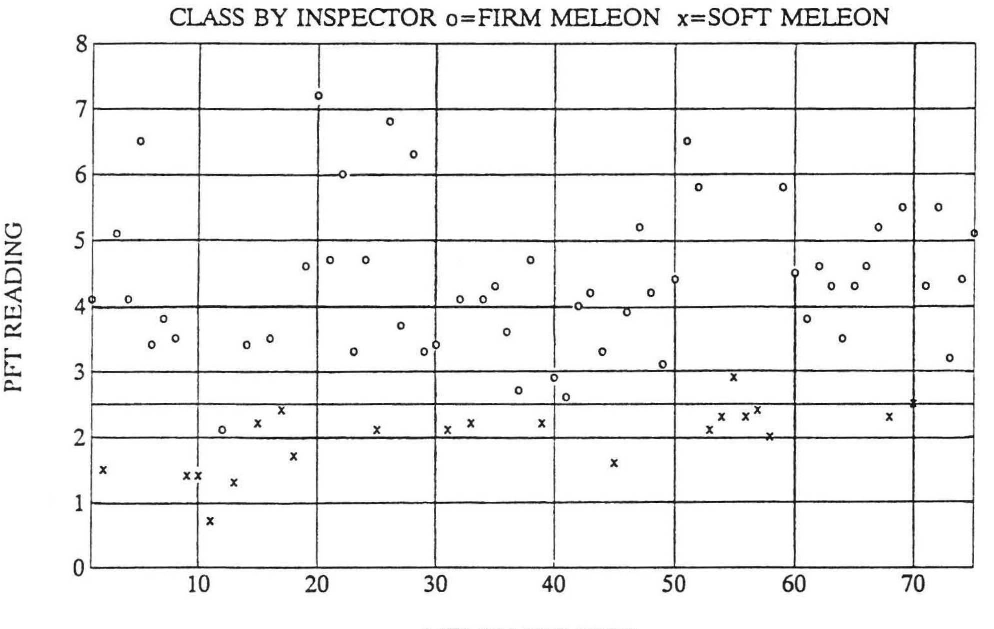

Fig. 5. Typical example of results obtained at a commercial quality inspection station wherein *PFT* readings on a sample of 75 melons are plotted, while those classified as 'firm' and 'soft' by sensory hand squeezing are marked by o's and x's, respectively.

DISCUSSION

Two softening phenomena may be observed, when assessing melon firmness by hand, as potential consumers might do when selecting a melon from a fruit stand or in a store. One is sensing the local resistance of the fruit to plastic deformation by thumb pressing, whence one assumes that the fruit is softer if the thumb pressure produces a larger local dent in the skin. The second is the overall stiffness of the melon that can be felt by squeezing it, similarly to the way one assesses the inflation pressure in a basket ball. Normally, progressive shelf-life reduces both the local resistance to plastic deformation and the overall stiffness of the melon, due to water loss by transpiration. We have observed that after extended shelf-life, wilted thick skinned melons may still show relatively high *CT* readings, even when their turgor is significantly reduced and internally off flavors render their flesh tasteless.

In the non-destructive sensor, the vibration energy must pass through the entire fruit, before it reaches, and is detected on its other side. The *PFT* readings are therefore a better indicat the global firmness of the fruit, as determined by its biological age after harvest, i.e., wilting and loss of turgor and overall stiffness. Thus, the new non-destructive sensor is better suitable for measuring post harvest softening of melons, both in terms of overall stiffness and loss of turgor, as well as resistance to plastic deformation.

Although it measures a different physical property of the melon, its readings are relatively well correlated to the piercing force obtained by the conventional destructive penetrometer method. The correlation is lower in thick skinned netted melons, wherein the penetrometer readings are biased by the strength of the skin.

Apart from being non destructive, the main advantage of the *PFT* is its ability to predict the expected shelf-life of melons.

If a sample of freshly harvested melons shows a relatively high mean *PFT* value, say *PFT*≈7.5-8.0, they may be safely shipped to a distant export market. Conversely, if the mean *PFT* reading of a melon sample is quite low say *PFT*≈4.5-5.0, their useful shelf-life will be limited to about 4 or 5 days so they should be sent to a local market.

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