Int. Agrophysics, 1994, 8, 431-437

A NEW SENSOR FOR NON-DESTRUCTIVE MEASUREMENT OF FRUIT FIRMNESS

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A b s t r a c t. A new sensor for evaluating fruit and vegetable firmness is presented while exemplifying application by reporting some results on measuring firmness of tomatoes. The firmness sensor comprises a small electrodynamic vibrator, which contacts the fruit and applies a series of minute input oscillations of a predetermined frequency and amplitude profile, optimized for each particular fruit type. These input oscillations are monitored by an acceleration transducer attached to the vibrator head.

The output oscillations on the other side of the fruit, are measured by a similar transducer attached to the sensor finger, which gently contacts the fruit by a controlled force. The signals from the transducers are acquired by a microcomputer, which computes a firmness index, based on the difference between the output and input oscillation profiles. Firmer fruits transmit a larger portion of the input signal than softer fruits. For quality control and shelf-life prediction, the firmness of tomato samples may be measured manually, by a bench-top version of the apparatus. For research and for optimal harvest time determination, the portable hand-held version of the apparatus may be used for monitoring the firmness of tomatoes as they grow in the field or greenhouse.

K e y w o r d s: fruits, sensor, firmness, non-de- structive measurement

INTRODUCTION

Traditionally, firmness measurements of fruits and vegetables are predominantly destructive, using penetrometr testers that measure the force required to penetrate to a given depth into the fruit flesh. In many fruit types it is desired to replace destructive measurement methods by non-destructive means, whereby the firmness of the same fruits can be measured repeatedly over the time span of its growth, storage and shelf-life, as well as sorting by firmness on packinghouse lines.

Most of the currently proposed non-destructive firmness sensing methods employ essentially three different variants of vibration response techniques for deriving fruit firmness indicators: a) Steady state vibration excitation below 5 kHz. b) Drop or impact induced vibration, while measuring the characteristic ringing response of the first half cycle, e.g., the coefficient of restitution or impact force. c) Vibration excitation in the ultra sound frequency band about 20 kHz.

In a 'pure linear resonator' impact induced shock may be considered as a special case of vibration, e.g., like in a ringing bell struck by a hammer. Unfortunately, most fruits and vegetables are not pure linear resonators, they exhibit rather non-linear stiffness and plastic non-recoverable deformations, at even modest shock inputs. Furthermore, most fruits exhibit at least two vibration modes, i.e. resonances. Relatively firm fruits, such as apples, melons, avocado, show three or four vibration modes, while in softer fruits like oranges, peaches, tomatoes etc. the second mode is much smaller than the first mode and the third and fourth modes are essentially attenuated by internal damping. The first mode, i.e. the lowest frequency mode may be excited by impact or by vibration, but it is very difficult to excite the higher frequency modes by impact without causing some damage to the fruit.

Impact excitation may be achieved by striking the fruit with a hard object or dropping it onto a hard surface, while vibration excitation is effected by placing the fruit on a shaker. The higher vibration modes can be easily excited by vibration with minimal input levels, so there is no damage to the fruit. To excite the higher frequency modes by shock in relatively firm fruits such as apples, the required impact, may cause significant plastic deformation, effectively preventing the higher frequency 'ringing'. Needless to say that the fruit may also be bruised in the process.

The typical form of the first resonance mode is characterized by localized deformations at the contact site of excitation, while the rest of the fruit moves as a solid body. In the higher modes, a larger part of the fruit vibrates, as vibration or shock waves traverse inside it. Thus, the first mode response is characterized largely by the local properties of the fruit at the contact site, while the response in the second and higher modes tends to be affected by the global properties of the entire fruit. Impact tests have been successfully tried by several researchers, on relatively soft and flexible fruits, such as oranges, peaches and cherries. These fruits behave much like rubber balls, whence the elastic recoverable deformation at the impact sites are relatively large even at small drop heights. This results in relatively large differences between the first mode amplitudes and frequencies of soft and firm fruits, thereby facilitating distinction between them, without too much damage. In less juicy and stiffer fruits such as apples and avocado, the recoverable deformations are much smaller, i.e., at impact levels which will not cause damage to the fruit. This means that the differences in the first mode frequencies of soft and firm apples are quite small, effectively precluding distinction between them. Generally, the second and third modes are much better for classification of all fruit types by firmness. In these modes, a larger part of the fruit is excited, creating an averaging effect, rather then focusing on the fruit properties at the contact site. The averaging effect is further enhanced in vibration excitation, by enabling examination of relatively long records, which include the response of the fruit to many input cycles, at different frequencies and amplitudes. This is impossible in impact excitation tests, where one can only use a single record of the first half cycle, or so.

Fruits are an extremely attenuating medium to vibration excitation at ultra-sound frequencies. Even when the power is very high, it is virtually impossible to transmit a realiable ultra-sound signal through fruits without employing a liquid coupling medium between the transducers and the inspected fruit. On the other hand, vibrations at frequencies below the 5 kHz range are readily transmitted by most fruits and vegetables. Ultra-sound frequencies are not only less suitable measuring fruit firmness, they are also much more expensive to implement and it would be very difficult to make them work properly in a packinghouse line.

In light of the above considerations, we have concentrated our efforts on firmness sensing by vibration below the 5 kHz range. These efforts are an integral part of our ongoing research program on Multi-Sensor-Adaptive-Sorting systems for classifying fruits by firmness, in conjunction with other fruit features such as size, shape, weight, colour, external blemishes and specific gravity.

STRUCTURE AND OPERATION OF THE NEW FIRMNESS SENSOR

This sensor 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 $\ddot{X}_0$ is measured by a transducer attached to a gripper finger contacting the top part of the fruit, whereby a firmness index PFT (Peleg Firmness Test) is derived by:

$$PFT = \ddot{X}_0 / (\ddot{X}_0 - \ddot{X}_i) \qquad (1)$$

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 relative PFT quantities are non-dimensional. A previous model of this sensor was extensively tested on firmness measurements of Red Delicious apples [3], and on avocado fruits [2]. Herein, a new improved model is presented while similarly reporting on its possible application for measuring firmness of tomatoes.

The table-top and portable hand-held versions of the new model firmness sensor are driven by a single plug-in card that can be fitted into any fully IBM AT compatible computer. The hand-held version may also be driven by a battery powered notebook computer, which has a suitable expansion docking station for an IBM AT compatible plug-in card. This facilitates the use of the portable hand-held model in the field or greenhouse, for monitoring the firmness evolution of fruits and vegetables during the growing and maturation stages.

A prototype multi-sensor machine was designed and tested by simulated computer animated operation, according to a US and Israeli patent [1]. This will soon be followed by construction of a laboratory size sorting machine incorporating the firmness sensor, whereby the feasibility of operation in a packinghouse line will be investigated.

RESULTS OF RIRMNESS TESTS ON TOMATOES

Similarly to previous tests on avocado, apples, melons, and strawberries, herein the new PFT model was used to measure firmness of tomatoes. To this end, a sample of 50 pink and 50 'ripe-green' tomatoes were especially harvested and stored at room temperature to hasten maturation and softening. Each tomato was identified by a number and four PFT readings were taken every two days, around the equatorial circumference, spaced about 90^o apart. Since the firmness around fruits is not uniform, the mean values of the four PFT readings were taken as more representative firmness values. The sites of the sensor finger contacts on the tomatoes were marked by a felt pen, to ensure repeated readings at the same locations on each fruit.

The initial PFT readings right after harvest on the 50 green tomatoes are marked by 'o' in Fig. 1 while the readings on the 50 pink tomatoes are marked by 'x'. It may be seen that by and large the green tomatoes were firmer than the pink ones, as may be expected.

The horizontal PFT=6.2 line in Fig. 1 was drawn to optimally separate the pink and green tomatoes, i.e., so the total amount of 'o' below and 'x' above it is minimized. Although this discriminated well between most of the pink and green tomatoes,some pink tomatoes ended up above it while some green tomatoes are seen below the PFT=6.2 line. This is in agreement with the well known observation that in a given lot, green tomatoes are not necessarily always firmer than pink ones. Thus, colour alone can not serve as a good discriminator between firm and soft tomatoes, but in conjunction with PFT readings, a machine can be built to separate tomatoes more accurately by colour and firmness simultaneously.

The superior sensitivity of the non-destructive PFT method to tomato aging, renders it particularly suitable for sorting tomatoes by predicted shelf-life. Freshly harvested tomatoes, that show higher PFT readings will generally have a longer shelf-life, as demonstrated in Fig. 2. In this test, the above sample of 50 pink tomatoes of various initial PFT firmness readings, were stored at room temperature, while taking consecutive PFT readings at the same locations on each fruit, every two days. In Fig. 2, the horizontal line of PRT=2 was chosen arbitrary, as a cut off firmness level which indicates the end of the useful shelf-life of these tomatoes. In practice, this cut off PFT level may be varied by experience,

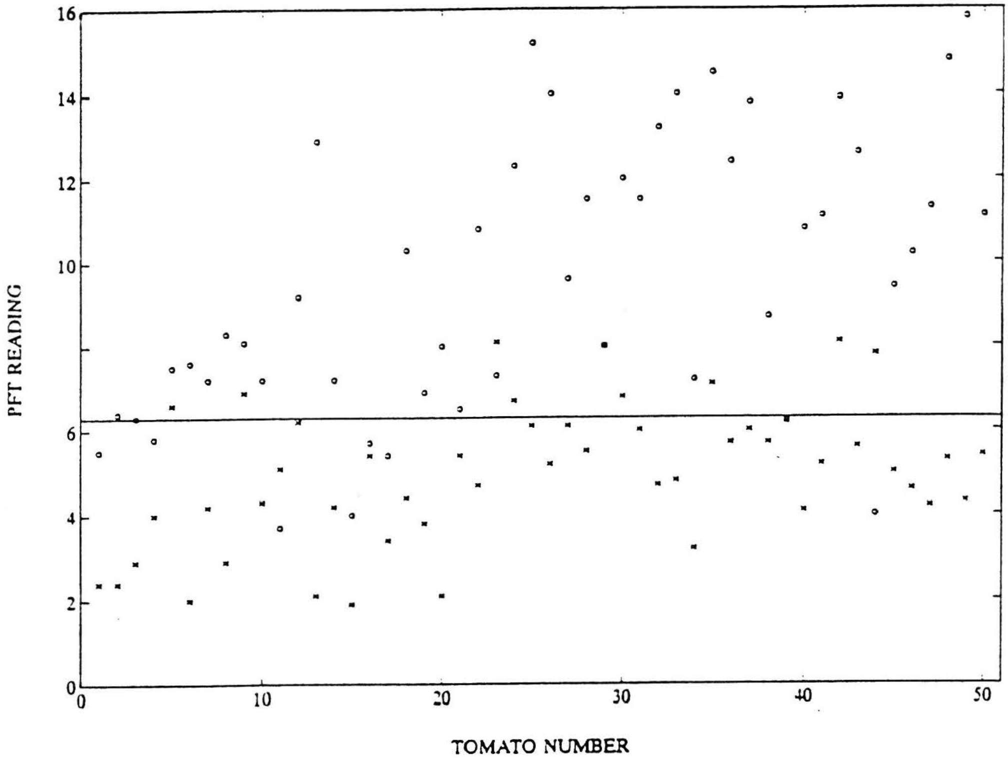

Fig. 1. Initial firmness of green (o) and pink (x) tomatoes.

depending on the tomato variety. When the PFT value of a tomato dropped below 2, 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. 2, it may be seen, that by and large, the shelf-life of firmer tomatoes is longer, as expected. The useful shelf-life of tomatoes with initial PFT values below 5 was about 2 to 6 days, as marked by the dashed lines, while the shelf-life of tomatoes that showed initial PFT readings of above 5, was about 8 to 20 days, as marked by the solid lines. Exceptions may occur of course, as demonstrated by the dashed lines of four tomatoes with initial PFT values below 5, which had rather long shelf-life, i.e., 10, 12, 14, and 17 days.

To investigate the firmness evolution of the ripe-green tomatoes as they turn to pink and eventually red and soft, a similar test was conducted on 23 most firm green tomatoes, selected from the initial sample of 50, as shown in Fig. 3. It may be seen that the initial PFT readings of these tomatoes was above 10 and after 40 days storage at room temperature most of the PFT readings dropped below PFT=2, which indicates very soft tomatoes.

It is interesting to note that during the first 2 to 4 days of storage at room temperature the green tomatoes soften rapidly and then their firmness increases during the following 4 days, in some cases almost back to the orginal firmness values. So far there is no explanation for this unexpected phenomenon. Perhaps horticulturists may be able to provide an explanation based on the biochemical processes during the maturation stages of green tomatoes as they turn to pink colour.

In any case, it is quite clear that the regime of firmness evolution of green tomatoes is

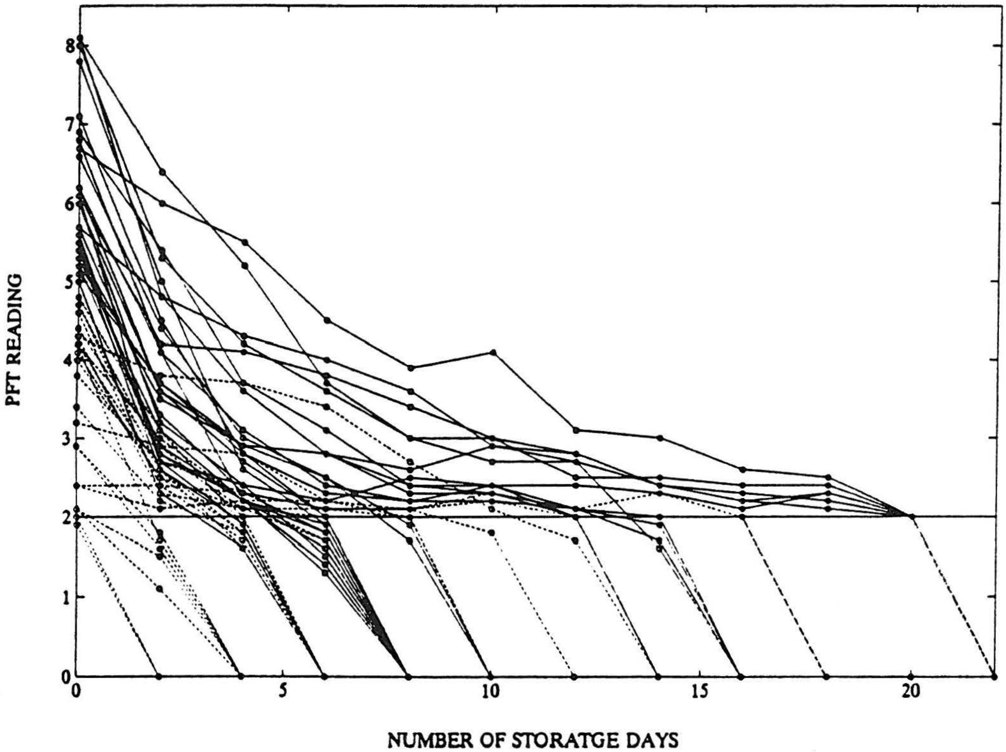

Fig. 2. Red tomato shelf-life at room temperature.

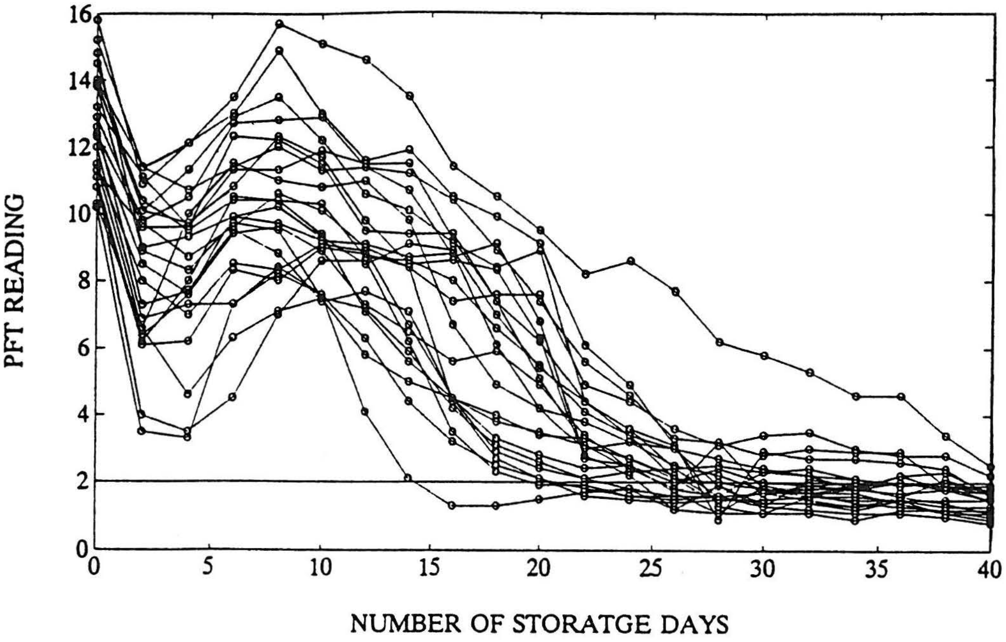

Fig. 3. Time spaced PFT readings on 23 firm green tomatoes.

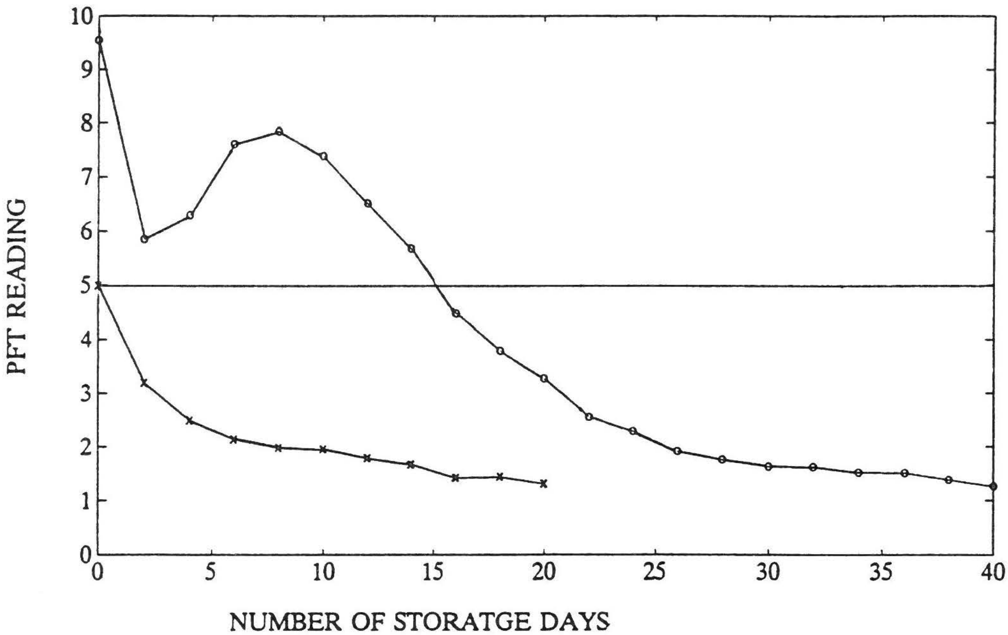

Fig. 4. Mean PFT readings on 50 green (o) and pink (x) tomatoes.

quite different from pink tomatoes, as demonstrated in Fig. 4. The bottom curve in Fig. 4 summarizes the time spaced mean PFT values of the sample of 50 pink tomatoes, while the top curve summarizes similarly the mean PFT values on the sample of 50 green tomatoes.

It may be seen that the initial mean PFT value of the pink tomatoes was about 5, so after the mean PFT value of the green tomatoes dropped to 5, their firmness reduction pattern was similar to the pink tomatoes. The green tomatoes reached the pink stage (mean PFT=5) after about 15 days of storage at room temperature. During the first two three days, the mean firmness of the green tomatoes dropped from PFT=9.5 to a minimum of PFT=6 and after 7 days of storage it increased back to a maximum of about PFT=7.8. During the following 8 days the firmness of the green tomatoes dropped almost linearly to PFT=5, whence their colour turned to pink. From the pink stage the firmness reduction was approximately exponential, as the pink tomatoes turn to red and very soft.

CONCLUSIONS

In summary of this study, we may conclude that the new non-destructive sensor is very efficient in measuring post harvest softening of tomatoes, in terms of overall stiffness and loss of turgor, as well as evolution of pink and red colour.

For quality control and shelf-life prediction, the firmness of tomato samples may be measured manually, by a bench-top version of the apparatus, which can be attached to a standard IBM AT compatible computer.

For horticultural research and determination of optimal harvest time, the hand-held portable version of the apparatus may be used for monitoring the firmness evolution of tomatoes as they grow on the wine, in the field or in the greenhouse.

Further research is planned for incorporating the new firmness sensor in a multi-sensor inspection and adaptive classification machine that can incorporate sorting by firmness in conjunction with the standard features which are now available from most companies, e.g., weight and colour.

ACKNOWLEDGEMENT

Gratitude is hereby expressed to Dr. Elazar Fallik of the Fruit and Vegetable Storage Department at the Volcani Institute, for his advise on horticultural of tomatoes and for providing the tomato samples for the experiments.

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