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Review article

Usage of fruit response to both force and forced vibration applied to assess fruit firmness- a review

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Abstract
Nowadays consumers are more cautious about quality of their foods. The attempts to assess the quality of food materials are numerous, but majority of these attempts are destructive to estimate fruit quality in nature. One of the most important quality variables is fruit firmness which is an indirect measurement of ripeness. In recent years, on one hand, nondestructive methods of fruit quality assessment have gained momentum; on the other hand, considerable assays have been made to expand these nondestructive methods. The number of method for quality assessment and classification of crops have been developed by several researchers over the past three decades. These methods are based on the detection of various physical characteristics which correlate well with certain quality factors of the products. The methods applicable to measure fruit firmness have been a noticeable target of interest for the researchers and farmers. This paper presents a review of various methods, which are based on fruit response to force and forced vibrations. These methods are: fruit response to force as: Mechanical Thumb, SIQ (Sinclair Internal Quality), Laser air-puff; detection by impact force as: usage Hammer measurement, usage Load Cell; Mechanical or Sonic Impulse methods as: usage accelerometer which includes PFS (Peleg Firmness Sorter) and Touchline method, Microphone, Piezoelectric film, and Ultrasonic vibration. Accomplishment methods for the fruit firmness evaluation are applicable, accurate, and sophisticated using methods are identified.

Keyword: Firmness, Internal Quality, Nondestructive, sensor.
Abbreviations: SIQ-Sinclair Internal Quality; PFS-Peleg Firmness Sorter; r.m.s-root mean square.

Introduction

Increasing demand of high quality fruit by consumers with the scarceness of labor in developed countries is promoting an advance in the expansion and development of sensors capable of measuring various quality variables in a non-destructive way during past few decades (Moreda, 2009). In the past few years, several authors have reviewed the main advances in this field. Studman (2001) reviewed the operations in the postharvest companies, where computers and electronic technologies have had a huge impact. Brosnan and Sun (2004) compared different computer vision systems for horticultural produce blemish and disease detection. Garcia-Ramos et al. (2005) reviewed non-destructive sensors that are used for evaluation of fruit firmness. Butz et al. (2005) and Nicolai et al. (2006) compared different technologies to characterize the internal quality (IQ) of fruits and vegetables. Moreda et al. (2009) reviewed non-destructive different technologies are used for fruit and vegetable size determination. The previous studies established that the IQ evaluation highly affects the fruit and vegetable post harvest period.

Fruit quality is related to some variables such as firmness, sugar content, acid content, and defects. Nowadays, increasing consumer demand for high-quality fruit has led to the development of acoustic, mechanical and optical methods that determine fruit quality (Roohinejad, 2009). Fruit packinghouses need to measure these quality variables, but they need to do so by non-destructive method. Packing companies and researchers have understood this and are currently developing sensors with this purpose (Garcia-Ramos, 2005; Soltani, 2010). Fruit firmness is one of the most important quality variables; it is an indirect measurement of ripeness and its accurate appraisal allows proper maintenance periods and optimal transport conditions to be established (Mirzaee, 2010). Texture is defined as a sensory attribute, and can only be measured directly by sensory means (Brennan, 1984). Firmness, which is also a qualitative concept, is only a small part of the sensation of texture in the mouth (Garcia-Ramos, 2005). Usually, fruit firmness has been calculated in a destructive manner by means of the Magness Taylor test (Magness and Taylor, 1925; barreiro, 1994). This test can be performed in the laboratory or with portable equipment, and is based on the introduction of a cylindrical head into the flesh of a peeled fruit to measure the maximum penetration force (Moreda, 2009). Depending on the equipment used, other variables can be measured such as maximum force, deformation, and the values for different relationships between force and deformation. However, the Magness Taylor test has three main drawbacks: it is destructive, measurements are highly variable (by up to 30%) (Barreiro, 1994) and it cannot be used in on-line situations. Nevertheless, this technique is well accepted and used for classifying fruit by many packing companies and quality laboratories.

Technological advances over the past few decades have led to the growth of non-destructive devices capable of measuring fruit internal variables. Initially, these were developed for utilize in the laboratory, but have been fitted for on-line use. This article describes various methods which are based on fruit response to force and forced vibrations which applied to assess fruit firmness.

○ Fruit Response to Force

Mechanical Thumb method

Evaluation of fruit quality based on fruit response to force consists of different methods; “Mechanical Thumb” is one of these nondestructive methods. It was first used by Schomer and Olsen (1962). Principle of this method refers back to destructive Magness-Taylor tester (Magness, 1925). Mattus (1965) reported that Schomer et al. (1963) developed “Mechanical Thumb” with a difference which a contact head of "mechanical thumb" replaced the standard plunger on the Magness-Taylor tester, and penetration was limited to 1.27 mm. Mizrach et al. (1985) used a small 3 mm diameter flat-head pin onto the peel of oranges and tomatoes and measured the force and deformation of the peel to estimate firmness of oranges and tomatoes. Tests showed linear relations between the elastic deformation and the load applied. Mizrach (1992) developed an on-line mechanical system estimate firmness by the use of "mechanical thumb" to compare the color of tomatoes. The difference between firmness means was significant at the level of 1%. All of the red-firm tomatoes in research of Mizrach et al. could easily distinguish from 100% of the green ones.

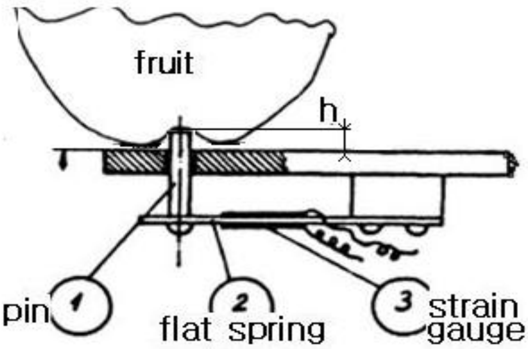

Fig 1. The Mechanical Thumb measures the deflection of the spring under load applied between pin and fruit (Mizrach, 1992).

Sinclair IQ^{TM}-Firmness Tester

Sinclair International has developed the Sinclair IQ^{TM}-firmness tester (SIQ-FT) that is based on a low-mass impact sensor (Howarth, 2002). This on-line system measures firmness by using a sensing element on the tip of a bellow. The element hits the fruit by air pressure and captures the responded impact signal (Fig 2), then makes four independent measurements (from four different quadrants around the fruit surface) that are combined to calculate the fruit IQ (internal quality). This device uses a particular data acquisition and data analysis to determine IQ of tested fruit. The fruit IQ is calculated according to the following equation as a dynamic measure of fruit tissue spring constant (~mm^{-1}):

$$IQ = C\left(\frac{P_{\max}}{\int p(t)dt}\right) \quad (1)$$

Where C is a system constant, P_{max} is the peak amplitude of the impact signal and $p(t)$ is the impact signal as a function of time (Shmulevich, 2003).

SIQ-FT takes advantage of Sinclair’s patented bellows delivery system, which is also used in fruit labeling and can be simply adapted to existing sorting lines. High correlation coefficient is obtained with penetration tests for nectarines (0.95), avocados (0.84) and kiwifruit (0.92). The SIQ-FT on-line system currently operates at speeds up to 10 fruits per second and is compatible with major sizing and grading equipment. According to the cited studies the impact techniques have obtained good results in the firmness prediction of some fruits such as pears, peaches and tropical fruits, but not in apples (Sinclair, 2009). Shmulevich et al. (2003) reported that SIQ-FT offers a different method that may overcome some basic difficulties associated by Ortiz-Canavate et al. (2001); Homer et al. (2002), when studying the performances of the low-mass impact test methods. The impact sensor that used in SIQ-FT is easy to apply and has the least sensitivity to variation in fruit shape, size and test location. Shmulevich

Fig 2. The Sinclair sensor hits the fruit by air pressure and captures the impact signal (Howarth, 2002).

et al. (2002) used a bench-top version of SIQ-FT in static form to measure IQ of apple.

Laser air-puff

Prussia et al. (1994) developed a nondestructive method for measuring the firmness of apple. This device (laser air puff) uses a brief puff of compressed air to deform the product surface about one millimeter (Fig 3), then a laser displacement sensor supplies a quick and accurate measurement of the deformation. At a determinate air pressure, the highest deformation of a firm product is less than for a soft product deformation. When another product with a different firmness range is used, the pressure is simply adjusted to the level required. The changing does not cause damage or defects to the fruit. Fruit stiffness value, which is defined here (Equation 2) as E_{puff} (the modulus of elasticity by the laser puff method), is calculated from the peak deformation measurement, D, by using a formula based on the Boussinesq theory of die loading (Mohsenin, 1986).

$$E_{puff} = \frac{P\pi(1-\mu^2)}{2D} \quad (2)$$

where P is the peak puff pressure on the fruit, μ is the poisson ratio and α is an equivalent die radius of the puff. The peak puff pressure P is calculated from the tank pressure P_{tank} by an empirically derived formula (McGlone, 2000). McGlone and Jordan (2000) used this method to measure firmness of apricot and kiwifruit and reported that Laser air-puff is only suitable for sorting fruits into two groups on the basis of firmness. Several steps are needed to get a firmness calculation. Product was located in the holder, which was put under the air nozzle, and the height was adjusted until a voltmeter connects to the output of the laser displacement sensor was zero. Regulator adjusts the air pressure at the predetermined pressure. Amount of fruit deformation due to air puff is measured by displacement of laser sensor and displays in digital oscilloscope and with this way estimates the fruit stiffness (Gunasekaran, 2001). Although this method has a high speed performance, but only very soft fruits can be accurately distinguished.

○ **Detection by Impact Force**

Instrumented hammer impact device

Most researches on the use of impact tests for the evaluation of fruit firmness employ the impact indices proposed by Delwiche et al. (1987). Results of previous studies show that impact techniques can be used to estimate maturity of fruits successfully (Garcia, 1988; Chen, 1993). A sample of this apparatus is shown in figure 4. This device consist of a low-mass impact hammer, a force transducer for to produce a miniature excitation, an electromechanical actuator and a 4-mm diameter hemispherical aluminum tip, which is used to produce the impact signal (Fig 4). Firmness is evaluated by following equations (Delwiche, 1987):

$$C_1 = \frac{P_{\max}}{T} \tag{3}$$

$$C_2 = \frac{P_{\max}}{T^2} \tag{4}$$

where P_{max} is the peak amplitude of the impact signal and T, is an impact characteristic time, such as T_p, time to peak amplitude, T_p, pulse duration, or T_m, width of the impact at half of the peak amplitude (Fig 5).
To estimate based on these parameters does not result in a promising accuracy of classification. A correlation of 0.75 was obtained for peaches in the research done by Delwiche et al. (1987). The method was soon implemented on an automated fruit sorter which gave a classification accuracy of 0.74 (Delwiche, 1989). When the falling impact was replaced with hammer impact, the classification accuracy was improved to 0.84 (Delwiche, 1991; Delwiche, 1996). In general, the use of falling impact in estimation of fruit firmness is superior to hammer impact due to simpler falling and sensing mechanisms which are more suitable for realization of on-line sorting (lien, 2009). The IQ impact parameters (C_1 and C_2) were not able to adequately predict the elastic modulus of the 'Starking Delicious' and 'Granny Smith' of apples (Shmulevich, 2003). Similar weak results have been obtained by Delwiche et al. (1991) for 'Red Delicious' apples, Ortiz-Canavate et al. (2001) for 'Golden Delicious' apples, and Homer et al. (2002) for 'Starking Delicious' apples.

Using load cell

One of the methods which is used to evaluate fruit firmness, is using load cell, and signal gets from load cell will be used to firmness assessment. The first systematic study of the load cell application to estimate fruit firmness was reported by Meredith et al, in 1990. In 1996 Molto et al, developed a sensor based on a load cell. The test fruit is located on a load cell plate and struck by a mass of 128 gram which falls from

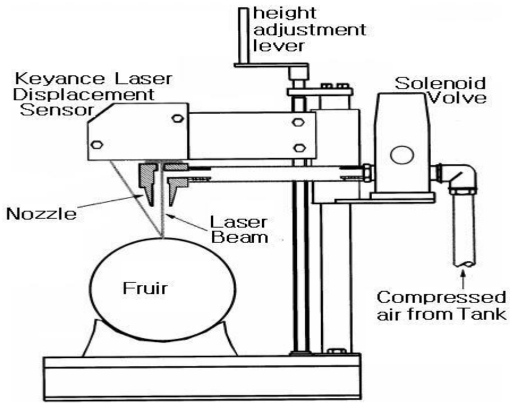

Fig 3. The nozzle of laser air puff is shown in cross-section with a shaded line following the vertical laser beam path to the fruit and then the imaging line (off-angle) back to the sensor (McGlone, 2000).

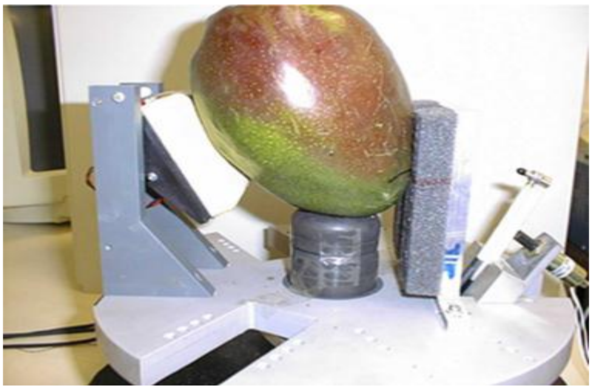

Fig 4. A low-mass impact apparatus used a 4-mm diameter hemispherical aluminum tip to produce the impact signal (Shmulevich, 2003).

a height of 1 centimeter onto the fruit. The signal supplied by the load cell measures the fruit firmness. Gutierrez et al. (2007) classified peaches in three categories (very firm, firm and not firm) by the use of load cell. Their device can work at a speed of 8 fruits s^{-1} and is able to classify peaches according to their firmness with 80% repeatability. Gutierrez et al. (2007) demonstrated that the load cell can be used to estimate fruit firmness. Lien et al. (2009) used this method to assessing the maturity of tomatoes. They classified the levels of maturity with cluster and discriminant analysis on the initial impact measurements and their derivatives. The apparatus consists of a pneumatic holding system, a load cell, a transmitter of impact signal, a digital oscilloscope, and a computer. A fruit is held by a pneumatic device released to fall freely. The falling height of fruit onto the load cell and the vacuum pressure were manually adjustable. The surface of the load cell, which receives the impact of the fruit, is made from stainless steel (Fig 6) (Lien, 2009). The best accuracy of classification is acquired 82.3%. Rangi et al. (2010) used a conveyer belt, which throws the fruit onto a flat horizontal plate connected to a load cell. They showed the impact device does not cause mechanical damage to the products (kiwifruits). In addition, they used free dropping of the fruit instead of throwing onto the plate by the conveyer, but did not provide a better prediction. The Most accuracy acquired in the research was 82.3%, too.

○ Detection by a mechanical or sonic impulse

Using accelerometer

The sonic vibration characteristics of fruits have been studied extensively by Abbott (1999); Peleg (1999). They showed that fruit firmness is highly correlated with a stiffness coefficient (Equation 5),

$$IF = f^2 m \tag{5}$$

where f and m are the second resonant frequency and mass of the fruit, respectively. Fig 7 describes schematic procedure of Peleg firmness sorter. The firmness sensor consist a small electrodynamic shaker, for vibrationally exciting the bottom part of the tested fruit. Fruit puts on a shaker and two accelerometers hold it (Abbott, 1999). The root mean square (r.m.s.) level of the input signal (X_i) is measured in the shaker head. The output r.m.s signal level (X_o) is measured by an accelerometer attached to the upper sensor (that contacting the top part of the fruit). The PFT firmness index is defined by:

$$PFT = \frac{X_o}{X_o - X_i} \tag{6}$$

Relatively firmer fruits pass a larger portion of the input vibration signal than softer fruits because the latter attenuate the input vibration energy more.

In 1985 Chen et al. developed an apparatus to measure fruit responses to impacts. The sensor consisted of a small, semi-spherical mass with an accelerometer, which was dropped onto the test fruit. Subsequent researches obtained better results by using a smaller impact mass (Jaren 1994; Chen, 1996; Chen, 1996). Afterwards, Garcia et al. (1988) used a new vertical impact sensor based on this system to measure the firmness of apples and pears (Jaren, 1992; Jaren, 2002)

Piezoelectric film

Fig 8 shows a Firmalon™ firmness tester. This device, which has been invented by Shmulevich et al. (1996), measured the acoustic response. This tester includes a force transducer to measure the fruit mass, a fruit-bed that equipped by piezoelectric sensor which enabled free vibrations of the fruit, and three electromechanical low-mass strikers to excite fruit vibrations. Present Firmalon™ is used to research and quality control of vegetable in maintenance procedure. A data acquisition program is used to select the lowest resonant frequency of the tested sample and calculate the acoustic firmness index FI (10^4 kg$^{2/3}$ s^{-2}):

$$FI = f_1^2 m^{\frac{2}{3}} \tag{7}$$

where f_1 is the first resonant frequency and m is the fruit mass.

In 2003 Shmulevich et al, used Firmalon™ to determine fruit quality changes during the controlled atmosphere storage. The results showed that the method may be effective to detect apple quality changes during the controlled atmosphere storage. This method was applied to evaluate firmness of three kinds of apple varieties ("Golden Delicious", "Starking Delicious" and "Granny Smith") by Shmulevich et al. (2003). Their results showed that this method might improve firmness estimation in "Starking Delicious" and "Granny Smith" apples. A similar device was used to assess peach

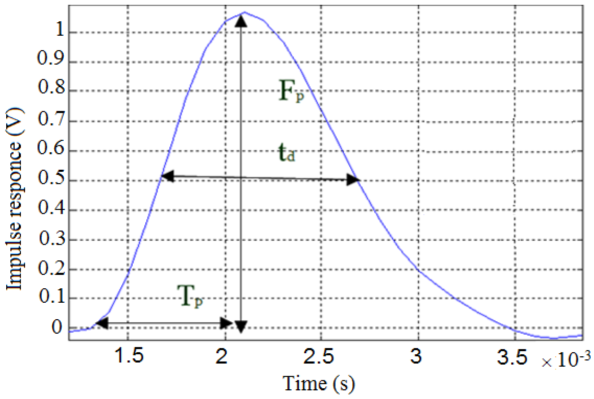

Fig 5. A typical acoustic signal of the instrumented hammer in the time domain and the utilized time domain harcteristics to evaluate the firmness (Shmulevich, 2003).

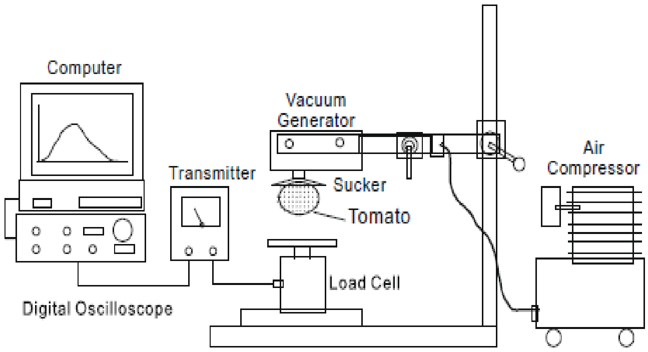

Fig 6. The test fruit is held by a vacuum sucker and released to fall freely from an adjustable height onto the load cell (Lien, 2009).

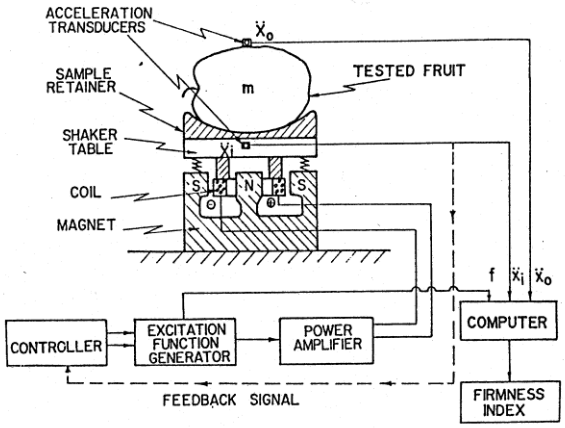

Fig 7. In PFS (Peleg firmness sorter), fruit puts on a shaker and two accelerometers hold it (peleg, 1999).

firmness based on piezoelectric sensor (Wang, 2004; Wang, 2006). The best relationship was obtained between dominant frequency and peach firmness (r^2=0.827).

Microphone method

Microphone method was presented by Yamamoto et al. (1980) first time. In this method, microphone is used to receive acoustic response. This method is quick because having no contact between sensor and product, but its accuracy does not have significant difference in comparison to soft piezoelectric film method (Shmulevich, 2003). Nowadays many researchers have shown an increased interest to use microphone method in their researches to classify pistachio (Ghazanfari, 1996; Pearson, 2001; Omid, 2009), to detect hollow heart of potato tubers (Elbatawi, 2008), classify hazelnuts (Onaran, 2004), discern between potato tubers and clods (Hosainpour, 2010), sort almond nuts (Ebrahimi, 2010), and grade mangos (Sugiyama, 2005). Distinction of sugiyama device is owing to the fact that it is portable (Fig 9). This method is applied for classification of peach, pear, pistachio, watermelon etc. Amoodeh et al. (2006) designed and developed an acoustic on-line grain moisture meter. Results showed that the accuracy of the sensor is affected by both sensor surface type and grain drop height. Khalifa et al. (2011) applied the microphone method to classify walnuts in three classes (fully developed, average, and empty). The microphone was installed inside an isolated acoustic chamber to eliminate environmental noise effects. The results of the research showed that the system accuracy to classify walnuts was 95.38%.

Ultrasonic

Fruit important features can be evaluated by ultrasonic nondestructive method. This method is based on energy transmission into product and evaluation of response energy. Mizrach et al. (1999) analyzed ultrasonic signals in avocado, to examine the influence of oil content and to nondestructively assess the avocado properties: maturity, firmness and shelf life. In nondestructive ultrasonic method, the pulser set causes the transmitter to oscillate and emits a narrow-band ultrasonic pulse into the fruit peel at a certain angle; this induced surface waves pass across the peel and fruit tissue, and activate the receiver (Fig 10). Mizrach et al (2000) used this method to study the impacts of storage time and temperature on softening process of the avocado fruits. Jivanuwong used ultrasonic techniques to detect hollow hearts in potatoes in 1998 and indicated that the accuracy of the detection would be improved if a smaller contact area for the transmitting transducer were used. Assessing the maturity and sugar content of plum fruit with an ultrasonic method was performed by Mizrach (2004). Reviewing the literature indicates that the ultrasonic method cannot be effectiveness to assess fruits and vegetables quality. This method is difficult to use in fruit quality determination since it is strongly attenuated when travelling through fruit tissues and as a result the ultrasound waves cannot penetrate deeply into the fruit.

Conclusion

In present paper considered several nondestructive method for agriculture product quality evaluation. Some methods are at upper level development than others. Because each method is based on measurement of a given physical property, the

Fig 8. The FIRMALON used three piezoelectric sensors to measure fruit firmness (shmulevich, 2003).

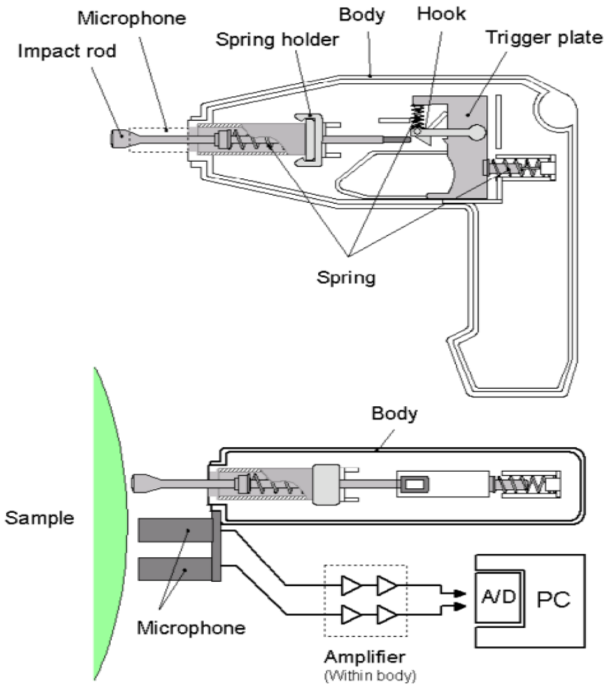

Fig 9. Mechanism of “Firm Tester” that used two microphones to evaluate firmness (Sugiyama, 2005).

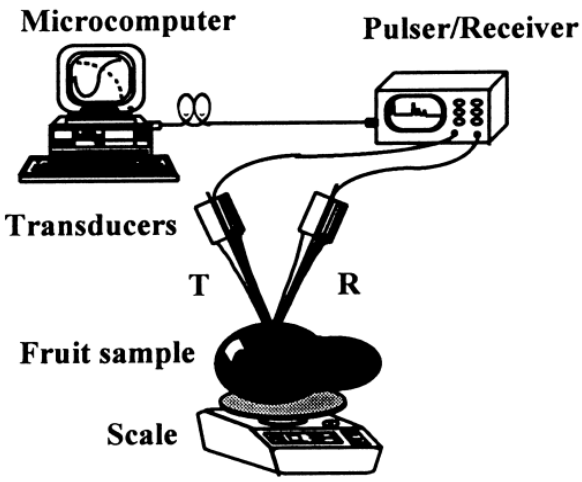

Fig 10. In the ultrasonic set, the transmitter and receiver are located at a certain angle (30^o) (Mizrach, 1999).

impressiveness of the method depends on the correlation between the quality factor of interest and the measured physical property. Also, researchers developed relation between physical features and quality index for more agriculture products. However, through use of computers and data analysis techniques, researchers have been able to reduce the effects of outsider factors and modify the correlations between some quality factors of interest and measured properties. Some methods have industrial application but others are in laboratory stages and them rapidity is a drawback for industrialize. Using new methods which increase accuracy and velocity and decrease costs could be useful in optimizing the detection of fruits firmness and internal quality.

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