I GEORGOFILI

Quaderni
2004-III

Giornata Internazionale di studio
su

NON DESTRUCTIVE TECHNOLOGIES FOR FRUITS AND VEGETABLES EVALUATION. COMPARISON OF EXPERIENCES

TECNOLOGIE NON DISTRUTTIVE PER LA VALUTAZIONE DEI PRODOTTI ORTOFRUTTICOLI. ESPERIENZE A CONFRONTO

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Indice

Giuseppe Pellizzi*

Ladies and Gentlemen, dear Colleagues,

I'm honoured to represent today professor F. Scaramuzzi, president of the «Accademia dei Georgofili», who, unfortunately, is not able to be here with us, due to other important duties.

The argument of this meeting is one of the most innovative because it tries to use new advanced technologies and systems based on electronic devices and instruments for evaluating the organoleptic properties of fresh fruit and vegetables, using non destructive methods.

The speakers of today - J. de Baerdemaeker, Belgium; M. Ruiz Altisent, Spain, I. Shmulewich, Israel and R. Guidetti, Italy - had the opportunity to work in the last few years for the development of technical solutions on this important and innovative topic. They worked independently but met each other in some meetings during which they had the opportunities to discuss and compare their results. So they decided to establish a co-ordinated activity in order to reach more quick and useful results of their work. In this, they found the important support of the Cesena Exhibition where had presented, in the different years, the progresses of their activities. Within this framework, with the consensus of the speakers, I have suggested to the president of the «Accademia» to offer the possibility to establish and support a permanent international working group able to obtain better and higher results. This proposal takes into consideration also the positive support of Cesena Exhibition as well as of UNITEC, Italian

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industry. Both, in fact, are co-sponsors with the «Accademia» that has organised this meeting. I want to express therefore our deepest gratitude to them.

Now I give the floor to the four speakers, who will be introduced with some general comments by a short presentation of my Colleague and friend Luigi Bodria, member of this «Accademia».

Thanks to all of them.

Luigi Bodria*

Introduction

Thank you Mr. President
it is always a great privilege to be here and speak in this prestigious building.

As previous mentioned by Prof. Pellizzi, there is a growing interest on qualitative selection of fruit and vegetable.

The demand for high quality products stimulated several researches, from the beginning of the 80's, to study and develop mechanical non-destructive systems for the assessment of the textural quality based on impact force and vibrations.

In recent years the development of computers and electronics promoted new studies on more sophisticated sensors and materials in order to detect internal quality like sugar content, maturity, absence of damages etc.

However fruit and vegetable market is a very important one in term of mass: the European production totals 147 millions of tons to which Italy and Spain together contribute for more than 30%.

In addition it is a market with a quite constant volumes of sales and therefore to stimulate the interest of the consumers with a certified high level quality offering an important added value to the products.

Moreover in the very competitive and dynamic large-scale retail trade fruits and vegetables play a strategic role in order to give a positive image of the store: they are generally nicely located at the entrance of the market as a sort of fresh and coloured welcome to the customers.

Quality is a very complex concept; the most common definition is "to meet

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the expectations of the consumers" but we don't have an average consumer and it is very difficult to define absolute quality parameters.

From an initial stage of the analysis of the external physical characteristics we are now investigating the internal fruit properties, but in the near future the attention will be devoted to safety, like absence of chemical residues, and to the health aspects, like proteins, antioxidants etc. to which the consumers will be more and more concerned and today we will have a very large and complete picture of the more updated researches on the field. Our speakers in fact represent some of the most active and qualified European laboratories dealing with this subject and they will offer us a deep analysis of possible future development of quality evaluation.

So I thank you for your attention and I give immediately the floor to our speakers.

Margarita Ruiz-Altisent*

New techniques for the evaluation of fruits and vegetables

1. PHYSICS IS THE FUNDAMENT

From decades ago, Engineers have been engaged in the development of new ideas for the harvesting and handling of agricultural products. During last century (1950 on) the need for creating mechanical harvesting and handling equipment for fruits and vegetables enhanced development and innovation in this area of knowledge and technology. The need for knowing the physical properties, mechanical properties at the time, grew urgent. Physics and mechanics, resistance of materials theories were there, to be applied to new materials, which are biological, living and changing with environmental conditions and with time.

Therefore, Engineers began to apply physics to agricultural products. Harvesting machinery was developed, for tomatoes, beans, greens, onions; fruits such as peaches, pears, prunes and other, for industrial processing were harvested mechanically, and were handled and packed for the market in industrial premises with fast and sophisticated equipment. Bruises, loss of firmness, and skin abrasions, causing pathogens to invade fruit, are caused by the equipment, and the means to minimise or protect the products of such had to be developed.

Properties of the product that relate to this kind of problems are resistance to damage, by impacts and by compression, properties of catching frames, and of damping materials. These are based on the knowledge on mechanical resistance named as resistance of materials. The theory of Hertz, relating to stresses pro-

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duced by contact between convex solids is still of use in solving this kind of situations.

Separation of residues and cleaning are based on size, shape, surface properties and by aero-dynamical (and hydro-dynamical) properties of each of the fractions which appear in the field: fruits, soil, clods, stone. These are separated by air currents, in which fluid velocity and ...caudal.....are the parameters being controlled in these systems.

At some point, the market, having achieved clean and healthy food, and in surplus quantities, begins to apply to highest value to quality.

2. QUALITY AS THE MAIN ECONOMICAL COMPONENT OF FOOD

Of course, it is of fruits and vegetables. Quality of fruits and vegetables is also related to their physical properties, as it is discussed below. Most of the properties that deal with quality are physical, or can be measured by physical instrumentation or based on physical sensing principles. Physical techniques include: Artificial vision; mechanical; acoustical; optical, magnetic resonance imaging, electrical techniques. The present techniques which are offered by the market will be discussed further.

3. PHYSICS NEEDS MAGNITUDES

A quality property can be expressed by a quality term, but to be measured it has to be expressed in a magnitude. When defining quality parameters and developing instrumental systems for measuring fruit quality, we need to distinguish four different concepts:

- first a '**property**', or quality property: it is rather an idea, well known by most consumers and experts, which lacks a precise physical meaning (for example: firmness or consistency);
- second a '**magnitude**', which is the value of a parameter with a defined physical significance and units; for example: puncture force (N) or force/deformation (N/mm); modulus of elasticity (N/m^2);
- third, we need the definition of a '**test**' and an instrument with a testing protocol: (for example: probe rupture by compression or by extension; Magness-Taylor or Effegi penetrometer; non-destructive impact or acoustic response meter); On the other hand, the property called "firmness" can be also determined by a magnitude defined as "stiffness factor" S ($kHz^2.g^{2/3}$), based on acoustic or vibratory response, or also by optical scattering coefficient; if

referring to external colour, parameter 'a', Hunter Lab, -10-+10 can be used, or a parameter based on a reflectance spectrum, measured with a SS detector Hammamatsu, in the range 200-700 nm.

- fourth, we need the definition of a '**scale**': the distance between consecutive divisions. Scales may be linear or non-linear; non-linear scales are usually the ones which relate best to sensorial perceptions.

A very important aspect of these magnitudes is the need to establish variability; metrology is study of the accurateness of measurements performed by any instrument, which leads to the determination of expected errors, and, most important, the error/range relation. On the other hand, there is the variability of the product itself, leading to the need to establish adequate sampling sizes for any application.

Quality of fruits and vegetables is made up by a combination of external and internal quality properties.

External quality properties are mainly: damage, colour and colour distribution, size and shape. The techniques used to detect them are:

- electronic fruits: used to assess damage inflicted to fruits by handling equipment
- artificial vision: to detect external damage, bruises, colour and colour distribution patterns, size and shape.

Internal quality properties are related to organoleptic or "consumers" quality features: firmness, sugar and acid content, internal colour, turgidity, juiciness, internal voids/ other discontinuities (seeds...), physiopaties (mealiness in apples, brown core...). To be determined, these defects need the use of

- electromagnetic radiation: optical, visible (VIS) and near-infrared (NIR);
- nuclear magnetic resonance (NMR);
- electrical (microwaves, MW);
- sonic response;
- sensing gases and aromas exerted by fruits during (post-harvest) ripening is of use for the assessment of quality of these commodities.

4. DAMAGE TO FRUITS BY HANDLING EQUIPMENT

Damage inflicted to products during harvesting and handling can be studied with the 'electronic fruit'. This instrument, a sphere with a sensor, a clock and a memory inside is programmed to acquire and register all impacts inflicted to it during its travelling in the (harvesting and) handling machines. It is very useful for the identification of critical points: transfer points where the fruit is subjected to damaging impacts with high/low probability. A graph of level and probability of impact can be established, so that the design of improvements in the machinery is made feasible. Also fruit-to-fruit impact can be established and improvement towards minimising them can be designed.

5. ARTIFICIAL VISION

It is widely used to establish external quality of products. Colour may be measured by RGB (red-green-blue) vision systems which have to be calibrated accordingly. It has been proved to work well for fruits with homogeneous colour such as *Golden* apples. These systems are far less developed and validated for bicolour fruits were there is a need of an accurate evaluation of colour distribution.

An artificial vision system needs first to grab the image, and second, to interpret its information: this last is called digital image processing. Image processing is a very active field of development, and nowadays a powerful software, Matlab, is widely applied for this purpose. Spectral imaging consists of acquiring and combining images at various short-band images, in one camera. This is a way to enhance defects (for example bruises in peaches) at grabbing. Using multi-image processing, as mentioned, opens a very effective way for external quality assessment of fruits and vegetables.

RGB vision systems are sometimes offered also assessing external defects. One major issue is to acquire all the external surface of the fruit. This may be attempted by rolling the fruit in front of the camera though never 100% of the surface is registered by this procedure. Another solution is the use of several cameras and mirrors to acquire several views of the fruit at the same time. The effectiveness is in general poor as it is difficult to avoid the interference of other external characteristics such as *russeting* in some apple and pear varieties. Also errors due to stalk and steam are found, when the fruit is not properly oriented before entering the sensing area.

Spectral imaging is a great development in fruit quality instrumentation and equipment. It consists of acquiring various images, at different (2-4) selected wavelengths and combining them in different ways. For example, bruises can be much better 'seen' by a camera when using spectral images at 920, 1040 nm than when using complete light. Pixel-by-pixel combination of these images is used for the development of parameters.

Also artificial vision is widely used today in on-line equipment for sizing.

Usually CCD (Couple Charge Devices) cameras are installed on every fruit line, with which size and shape are determined for grading fruit according to standards. The present need imposed by the manufacturers for an output of 6-10 fruits per second seems rather difficult to match the precision in size grading (1-2 mm in diameter in oranges) imposed by standards. Shape and size can be also established using a new optical device, the "optical ring" sensor (Moreda et al. 2004). Volume and diameters, especially for spherical and elongated products are accurately determined at high speed.

6. MECHANICAL PROPERTIES AND INSTRUMENTS: FIRMNESS

There exist a very wide selection of instruments to measure firmness. The penetrometer (Magness-Taylor) is the oldest and most accepted by common users, and most ejected by engineers and physicists. This test has never been studied with metrology protocols, as no reference material is available for it. It has many problems of reproducibility, and concerning the range of validity. The rest of firmness-measuring instruments are considered non-destructive or "contact" based. We have: acoustic resonance (AIR-KU Leuven), impactometry (LPF-UPM), Durofel (Copa-Technology), and ultrasound (TECHNION and the Volcani Centre). Each of them yield different magnitudes, which are loosely correlated to destructive penetrometer values, as they measure rather deformability, more closely related to hand-held sensory appreciation. Destructive penetrometry resembles more to 'biting' firmness. Correlation between the Magness-Taylor

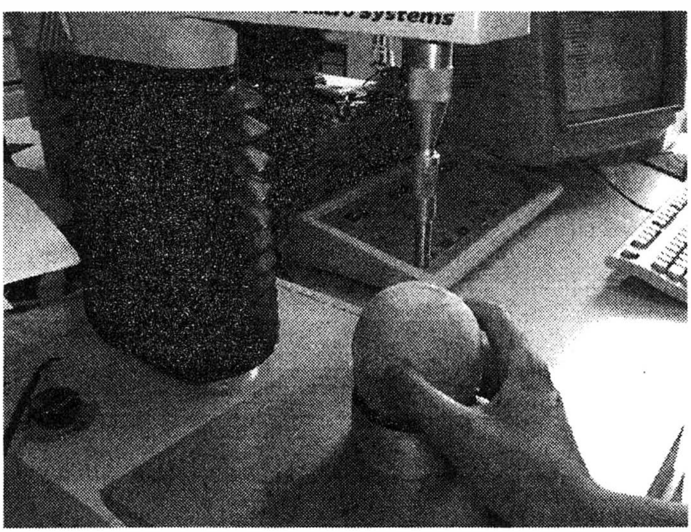


Fig. 1 *Laboratory equipment for firmness measurements: Texture Analizer, by stable Systems force and deformation can be measured*

penetrometer and other non-destructive firmness instruments improves when using penetrometer force/deformation ratio rather than force. However, this parameter can only be registered through automated "universal" or "texture" tests and not with manual instruments.

7. ELECTROMAGNETIC RADIATION

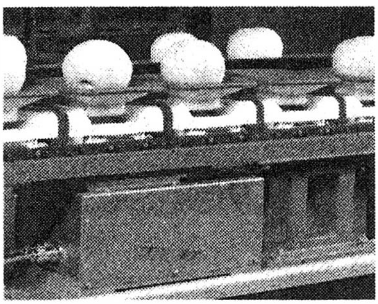
The electromagnetic spectrum is received in the Earth from the external space, and it can be also created by man-made devices. Optical radiation is the one that can be managed with lenses. From this, VIS and NIR are easiest and cheapest, to be used in instruments for quality measurement of many different commodities. Electromagnetic radiation interact with matter: it is transmitted, reflected, refracted, absorbed, transformed into different wavelengths, or different types of radiation. Interaction with biological solids, such as fruits and vegetables, is therefore very complex, due to complexity of their structure: cells, cell components, skin, etc. (Bellon et al, in Hildrum ,1992). Also, most of the fruit is made of water. The response spectra that can be obtained are mainly of water, with some small variations which can be assessed using powerful numerical and statistical methods; on this basis, models for the estimation of quality attributes such as soluble solids (SS), acid content, physiological disorders can be developed. Molecular groups and individual molecules absorb in some of the wavelengths of interest, and therefore they can be detected; for example, methyl acetate absorbs at approximately 5800 and 8000 nanometers and methyl ethyl ketone shows two absorbing peaks at very near areas. Such molecular groups are very mixed in biological materials, so that spectral absorbance and reflectance are not resoluble in chemical means (Bonanno, et al, in Hildrum 1992). SS and acids may be detected mainly because they reduce the quantity of water.

Procedures to extract information of the data obtained from the response spectra are now relevant developments; modelling and decision rules are applied to the calibration of any type of instrumentation. The process of calibration is critical, and in this, self-learning and error-detection algorithms are needed, for the user friendliness. Coming to the applications, special features are of great importance: the range of variability of samples used for calibration and of product batches to be graded have to be matched; the experience shows that various years of use of those models are needed to reduce estimation errors. Errors are established using metrology; important parameters to be established are accuracy, repeatability, sensitivity and robustness.

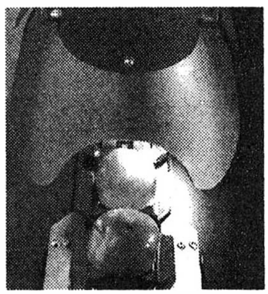
On-line optical transmittance equipment is being commercialised for the detection of internal quality estimation in fruits. This equipment uses very near (or short-wave) infrared (650 to 1200 nanometers approx). Much information is and can be captured at the low-end, related with absorbance by chlorophyll and other pigments, and therefore related to ripeness advancement and internal breakdown or vitrescence, for example in melons. On-line measurements are an alternative to at-line tools; in on-line equipment the totality of the product is evaluated one by one at the packing house machinery. Obviously, it is a very desirable situation but it is not available for all quality parameters.

A discussion is being raised regarding effectiveness of commercial equipment, based on optical and mechanical sensors for on-line internal and external quality assessment. Some of this equipment is very well designed for their purpose, but lack of standardisation, mainly of testing protocols, is an important drawback which prevents the generalization of the technique for market actors. There is a real need for determining the procedures for calibration and validation processes of the equipment.

For **on-line measurements** there is the need of: 1) high speed and 2) non-destructive techniques. At current stage packing lines work at 15 t/h approxi-

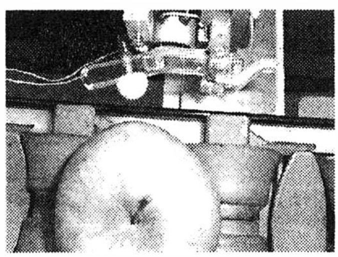


Load Cell for fruit weighting (MAICI)



Reflectance NIR spectroscopy for on-line soluble solid estimation (COMPAC)

Transmittance NIR spectroscopy for on-line soluble solid estimation (FANTEC)



On-line impactometry to assess firmness (LPF)

Fig. 2 *On-line measuring systems: Load cell, impactometry and NIR spectroscopy* mately which correspond to 5-10 fruits/second for small size fruits (apples, peaches...) or 2-4 fruits/second for large size fruits (melons...). It could be discussed the need of slowing down a bit the current grading lines also as a method to reduce damages, but in any case the bottom limit seems to be around 3-5 fruits/second. In any case, laboratory instrumentation has to be available, to be used as reference for the development of online equipment. In many cases, this instrumentation needs to be established in accordance to consumers perception of any quality attribute.

New optical technologies are also at development stage to be mounted on line such as X-ray and NMR for internal quality sensing, or new optical devices for 3D size evaluation. The main objective of this and other techniques is the assessment of the whole fruit. A technique called **TDRS** (time-domain diffuse reflectance spectroscopy), evaluated in the European Project FAIR CT 96 1060), is being tested with some success. It uses VIS and NIR lasers at various wavelengths applied through a single optical fibre, and detection is accomplished by photon-counting equipment. It differs from the conventional optical equipment in that it assesses both absorbency and scattering of light in a differential way, in principle allowing textural and chemical evaluation independently. (Barreiro et al, in Dris, 2004).

Sensors and sensors arrays for detecting **gases and aromas** are being developed as a technique for quality monitoring in control; the application is near for in-transit and storage detection of possible problems in fruits and vegetables. **Microwaves**, is a promising new (electrical) technique, showing promise mainly for pathological treatment of plants, mainly insect plagues. Soft X-rays are being studied heavily for internal damage detection in apples, citrus and tomatoes.

8. Areas of development for the (near) future

Apart from the mentioned new techniques, such as NMR, soft X-rays, acoustics and laser applications which are at laboratory stage at present, the new envisaged area comes in hand with Biotechnology. The development of biosensors of many kinds, molecular (DNA) arrays, biotechnology new processes, etc... will need the cooperation of product-related Physics and Engineering in the very near future.

The Physical properties Laboratory (LPF) at the Polytechnic University Madrid is specialised in research and development, as well as innovation, on properties of –mainly- fruits and vegetables related to their quality. It carries out design of improvements in harvesting and handling systems, and in the development of instrumentation, at- and on-line for measuring product quality. Techniques used include mechanical, acoustical, optical: VIS, NIR, image, gas sensing, NMR.

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Josse De Baerdemaeker, Sandra Landahl and Bart De Ketelaere*

Non destructive measurements and quality evolution models for fruit shelf life prediction

1. INTRODUCTION

High quality standards and the necessity for shelf life determination have increased the need for simple and quick evaluation of the internal properties of each product sold, preferably making use of non–destructive devices that 'sense' the product's quality attributes such as firmness or flavor (Galili and De Baerdemaeker, 1996).

For firmness, several sensors have reached the commercial market, and are based on impact analysis or vibrations (acoustics). Although those sensors have proven their merit in lab scale experiments, the critical mass still needs to be convinced; people are for many years used to older, standard techniques such as Magness Taylor (MT) type of devices, and are reserved in accepting the newly developed sensors that express firmness in different units, on different scales. From literature, it was found that the fruit firmness was highly correlated with the stiffness coefficient S resulting from the acoustic sensor, defined as f^2m, (Abbott et al., 1968) with f the natural frequency of the elliptical mode shape of the fruit and m its mass. This stiffness factor was later modified by Cooke (1972) who showed that the mass correction factor was $m^{2/3}$ rather than m. These formulas hold for spherical fruits. Yamamoto et al. (1980) developed an acoustic impulse-response method for which the fruit was excited by an impact with a small pendulum and a microphone was used as contactless response sensor. They showed that the resonant frequencies and firmness indices, expressed as func-

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tions of the resonant frequency, mass and fruit density, are significant correlated with fruit firmness and sensory measurements. The stiffness coefficient S was significantly correlated with fruit firmness and sensory measurements (Van Woensel et al., 1987; Abbott and Lu, 1996). The first part of this text will be devoted to the comparison of the results of such an acoustic sensor with those of the classical MT firmness for internal damage of apples.

The advantages of having a non destructive sensor reaches far beyond the fact that it is just non destructive. Indeed, they offer the possibility towards monitoring individual products during the experimental period, which on its turn allows for modeling the quality change with a limited number of fruits to be tested. The modeling of the quality evolution of horticultural products during storage has been described in literature by several authors (Jackman et al., 1990; Thai and Shewfelt, 1990; Chen and De Baerdemaeker, 1990; Chen et al., 1990; Chen, 1993; Rosenfeld et al., 1994; De Belie et al., 2000). The repeated measurements nature of such data, their heteroscelasticity (non constant variance) combined with the large natural variation necessitates a very specific data analysis that reaches beyond the often-used methods in literature such as an analysis of the quality at each time point, or an ordinary least squares regression model. Laird and Ware (1982) proposed a statistical model that allows for a subject–specific effect above a population–specific effect. These subject–specific regression parameters reflect the natural heterogeneity in the population and can also be interpreted as the deviation of the evolution of a specific subject from the overall population. This type of model is called mixed–effects model and is appropriate for data that exhibit a large inter–subject variability, as is expected for measurements on biological produce. Furthermore, the incorporation of, for instance, a subject–specific time trend allows the variance of the data to change with time which is in many cases a realistic issue.

2. COMPARISON OF METHODOLOGIES FOR INTERNAL DAMAGE OF APPLES: ACOUSTIC IMPULSE RESPONSE VERSUS MT FIRMNESS

Sumnu (2001) explains that in a microwave oven heat is generated because of the inability of rotating molecules to keep pace with the alternating field. Because of its dipolar nature, water, the major constituent of most food products, is the main source of microwave interactions with food materials. Relatively large amounts of internal heating seem to result in increased moisture vapor generation inside a solid food material, which creates significant internal pressure and concentration gradients (Sumnu, 2001). This might lead to cell damage. Physicochemical changes can not always be completed during microwave heating (Sumnu, 2001). Thus, like in the bruising process the damage might develop gradually. The cool ambient temperature inside a microwave oven causes surface cooling (Sumnu, 2001). Possibly this preserves the outer layers of the apple tissue from heat damage after short microwave treatment. Hence, microwave treatment seemed a suitable technique for inducing internal damage in the fruit.

A hundred apples half from the cultivars 'Elstar' and 'Jonagored' were divided into 4 groups of 25 samples. The apples were provided from ultra-low-oxygen storage by the laboratory of postharvest technology of the Katholieke Universiteit Leuven, Belgium. The MT firmness was examined first. Two spots on the equator plane opposite to each other were measured with a universal testing machine (UTS5, Testsysteme, Ulm, Germany). An arched plunger was used to cut through the skin of the apple. The test was done with a 11 mm probe to a depth of 8 mm at a speed of 480 mm/min. The whole apple was supported by sand in a bowl to achieve a maximized contact area opposite of the measurement. The maximum force during this test, which was measured by means of a 200 N load cell, was recorded. Then the stiffness factor or acoustic firmness index was obtained by the acoustic impulse-response technique. This was achieved by means of the commercially available acoustic firmness sensor (AFS, Aweta™, Nootdorp, Holland), which was partly developed in the laboratory for agricultural machinery and –processing, Leuven, Belgium. Two hits on undamaged spots on the equator plane were done per fruit.

All 100 apples were subject to microwave treatment to obtain fruit with internal damage. One group of 'Elstar' apples was heated once for 30 s in a microwave oven at maximum power (AEG™, FX30Z-sp, 1300 Watts, 2450 MHz). The other 'Elstar' group was treated for 30 s first. All apples were put back into the cool cell for at least half an hour between microwave treatments (2° C, 90 % relative humidity). The second 'Elstar' group was put back into the oven again for 20 s. Each apple was put in the centre of the bottom of the microwave oven. This way each apple was given the chance to absorb approximately the same amount of energy. One group of 'Jonagored' apples was treated 40 s and then 40 s again and the other group had the strongest treatment with 30 s, 50 s, and then 30 s again. Apples were first put on the calyx end, then the stem end, and then the calyx end again to vary the orientation of the apple.

After the microwave treatments the apples were allowed to cool down in the cool cell for at least 30 min. Then they were measured with the AFS again to compare the stiffness values before and after the heat treatment. Also the MT firmness was measured again. Two undamaged spots on the equator plane of the apples were tested, located in about a 90° angle to the first 2 indentations. Before comparing the MT firmness before and after microwave treatment an average of the 2 measurements on opposite sides was made in order to obtain a global value. Statistics were performed in Microsoft™ Excel©.

In the 3 apple groups tested for MT firmness no significant difference was found between apples before microwave treatment and after (Table 1). One group of the 'Jonagored' apples was not punctured to make sure there is no influence on the results of the acoustic test. With the acoustic impulse-response technique highly significant differences were found between the control and the measurement after microwave treatment. Due to a malfunction no control stiffness factors were available for one group of 'Jonagored' apples. Therefore the t-test was performed with the control values of the other 25 'Jonagored'.

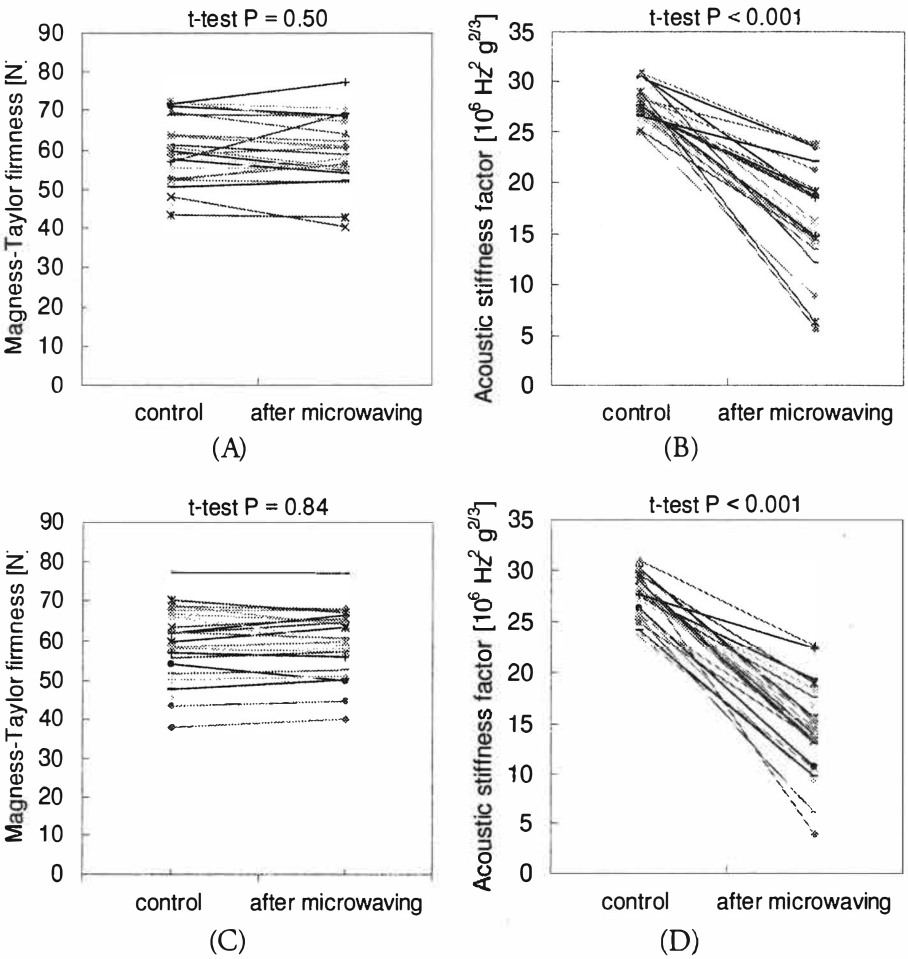

Fig. 1 *Firmness (A & C) and stiffness (B & D) change before and after microwaving. (A) & (B): Elstar, 30 seconds; (C) & (D): Elstar, 30 + 20 seconds*

Table 1
Results of t-tests performed on firmness and stiffness values before and after microwave treatment

t-test P =	F max	stiffness
	paired	paired
Elstar 30	0.50	< 0.0001
Elstar 30+20	0.84	< 0.0001
Jonagored 30+50+30	-	< 0.0001
	paired	heteroscedastic
Jonagored 40+40	0.73	< 0.0001

A graphical representation of the results for the Estar apples is provided in Figure 1 where it can readily be observed that the stiffness of the apples decreases after treatment, but that the firmness did not change. An explanation of this phenomenon may be the following. Microwave heating may cause water loss, caramelization of sugar, or cell damage and cause browning. Dehydration and cell rupture seem the most likely to change the apples' stiffness factor. Since the acoustic impulse-response technique is a global test, damage inside the apple can be detected. On the outer pericarp the apple seemed undamaged as the local MT firmness measurement indicated.

3. Shelf life prediction models based on repeated measures

Shelf life prediction is an important issue for fruit handling. As mentioned in the introduction, not only the average quality trajectory a batch follows needs to be estimated, but also how much the quality is dispersed around the batch average since we are generally interested in an estimation of the time at which, for example, 5 % of the fruits reach a pre-set lower bound for their quality. In order to stress the importance of the variance, a graphical representation of the behavior of three batches that follow an identical average sigmoidal change (shown in the left two columns), but have a different amount of biological variability was made (Figure 2). The left column shows the quality decay in a broad time window, while the middle column only shows the decay during 15 days. On the right of the figure the theoretical change of the quality distribution of the three batches is given, from day 1 to day 15. Those theoretical distributions are calculated assuming that the different fruits in the batch show a normally distributed 'shift' of their quality decay. It can be observed that the variability of each single product within the batch has a tremendous effect on the batch quality distribution at a certain time point.

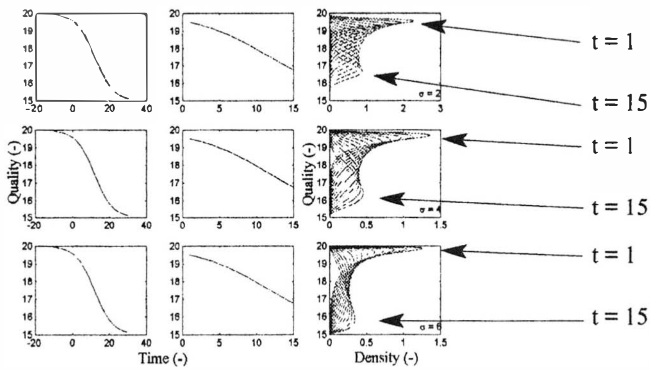

Fig. 2 *Quality change for three batches. Upper row: low batch quality variability; middle row: average variability; lower row: high variability. Left column: average logistic change; middle column: average change between day 1 – day 15; right column: superposition of the theoretical density functions from day 1 to day 15*

In view of this issue, it is of utmost importance to correctly treat biological variance when modeling fruit quality changes and making shelf life predictions. An appealing and flexible way to account for the biological variance and the repeated nature of the data is making use of the concept of mixed models. In its general form, a linear mixed model can be written as

$$Y_i = X_i b + Z_i b_i + e_i \qquad (1)$$

with Y_i the n_i–dimensional vector of all repeated measurements for the i–th subject (fruit); X_i the $(n_i ' p)$ design matrix of known covariates; b a $(p ' 1)$ vector of fixed effects; Z_i a $(n_i ' q)$ matrix of known covariantes (for instance storage time) modeling how the response evolves over time for the i–th subject; b_i a $(q ' 1)$ vector of subject specific effects for which is assumed that $E(b_i) = 0$ and e_i the vector of residual components e_{ij}, $j = 1,\ldots,n_i$. The random effects structure implies a covariance structure of a very specific form

$$Var(Y_i) = V_i = Z_i D Z_i^T + S_i \qquad (2)$$

where D refers to the variance–covariance matrix of the random effects. It can be seen that the total covariance structure is partly determined by the Z_i vector of random effects and partly by the error variance–covariance matrix S_i. Remark that this structure allows for heteroscedasticity as function of time. In other words, we allow the data variability to change over time, which is in most practical datasets true. For details on model building issues, see De Ketelaere et al. (2003).

We will illustrate the flexibility of such model using a practical example. Tomatoes of 13 different cultivars were harvested and their firmness was followed during 2 weeks of storage. The data were measured at the Flanders Centre for Postharvest Technology (Leuven, Belgium). For each cultivar, 20 tomatoes were analyzed for two harvest periods, August and October. Tomatoes were stored at controlled atmosphere conditions (18 °C and 80 % RH) to accelerate the ripening process. Tomato firmness was assessed using a commercial acoustic firmness tester (AWETA, Nootdorp, The Netherlands). Stiffness was measured three times at the south pole of the tomatoes for each measurement day. In the remainder of the text, the term stiffness will be used when indicating values produced by the acoustic tester and which are an estimate of the firmness. The data were fitted using an extension to the first order degradation model, see De Ketelaere et al. (2004). It includes an intercept, slope and quadratic trend for each harvest ′ cultivar combination, together with a random intercept, slope and quadratic trend. With this model, the total data variability was split up into the following components: (1) inter-tomato variability (batch variability); (2) intra-tomato variability (measurement error) and (3) residual variability, i.e. variability not captured by the model. These results are graphically presented in Figure 2.

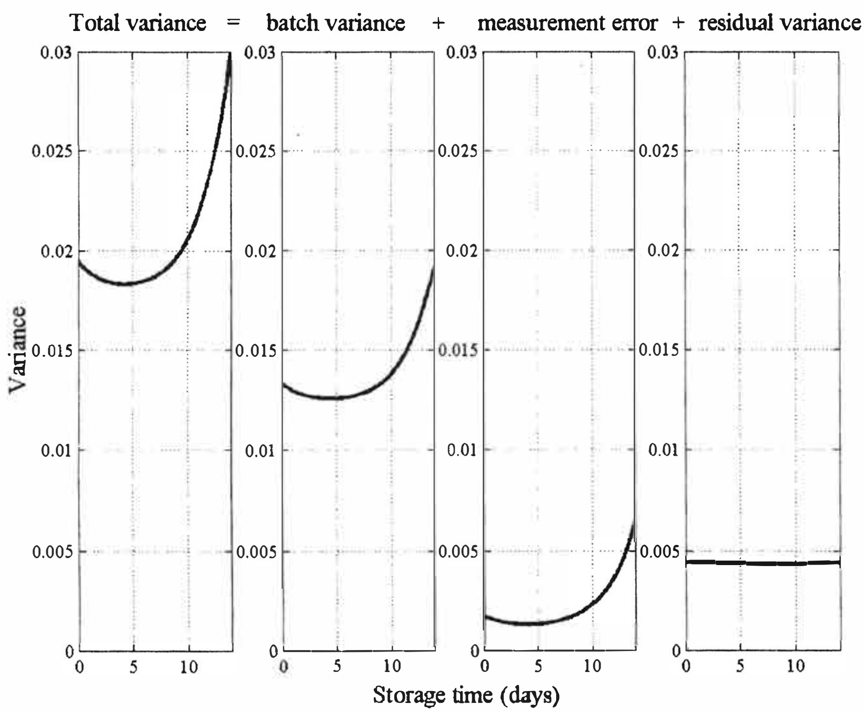

Fig. 3 *Decomposition of the total variance as function of storage time into its three components*

At harvest, the variance of the three measurements is 0.0017 units on logarithmic stiffness scale and increases almost four–fold to 0.0066 after two weeks of storage (Figure 2). For instance, for a tomato with stiffness 8 ′ $10^6 Hz^2 g^{2/3}$ at harvest, the 95 % confidence limits for its stiffness are 7.68 to 8.32 ′ $10^6 Hz^2 g^{2/3}$. For a tomato with a stiffness of 5 ′ $10^6 Hz^2 g^{2/3}$ after two weeks of storage, its 95 % confidence limits are 4.40 and 5.60 ′ $10^6 Hz^2 g^{2/3}$, a substantially broader interval than at harvest. As such, they provide an estimate of the repeatability of the acoustic firmness tester.

A visualization of this model for selected cultivars is provided in Figure 3. The *Y*–axis was kept fixed between 3 and 8 ′$10^6 Hz^2 g^{2/3}$ for all plots in order to make visual comparisons between tomato cultivars more straightforward. Comparing both harvest periods for all cultivars, the initial stiffness of the October harvest is higher than for the August data. A second remarkable feature is that, due to the inclusion of a quadratic term in the log–linear model, some tomato varieties tend to keep their stiffness rather constant during the first days of the experiment, but the decrease is much more pronounced near the end of the study (Figure 4). On the other hand, some varieties tend to loose their stiffness very rapidly at the start of the storage experiment, but exhibit a quasi constant stiffness at the end of the study.

Using such a mixed model, one can have an estimate of the time at which a certain percentage of fruits reach a critical quality (shelf life). This can by achieved using the delta rule, or by Monte Carlo simulation (De Ketelaere et al., 2003). The shelf life for different cultivars is given in Table 2. It can be observed that shelf life varies remarkably among cultivars. The values obtained as such (using the mixed model) take into account the repeated nature of the data and the special variance structure depicted in Figure 3. Values for the shelf life obtained using classical regression would be misleading due to the incorrect assumptions of such model, such as constant variance and independence among measurements.

Table 2 *Shelf life values defined as the time at which 5 % of the tomatoes reach a critical firmness value of 5.5 ′ $10^6 Hz^2 g^{2/3}$ for selected cultivars. "+" indicates that the shelf life is longer than the experiment duration (14 days)*

cultivar	harvest	shelf life (days)	cultivar	harvest	shelf life (days)
BS9445	August	3.0	DRW6340	August	2.0
BS9445	October	7.5	DRW6340	October	3.5
DRW5736	August	7.2	DRW6391	August	+
DRW5736	October	10.2	DRW6391	October	13.8

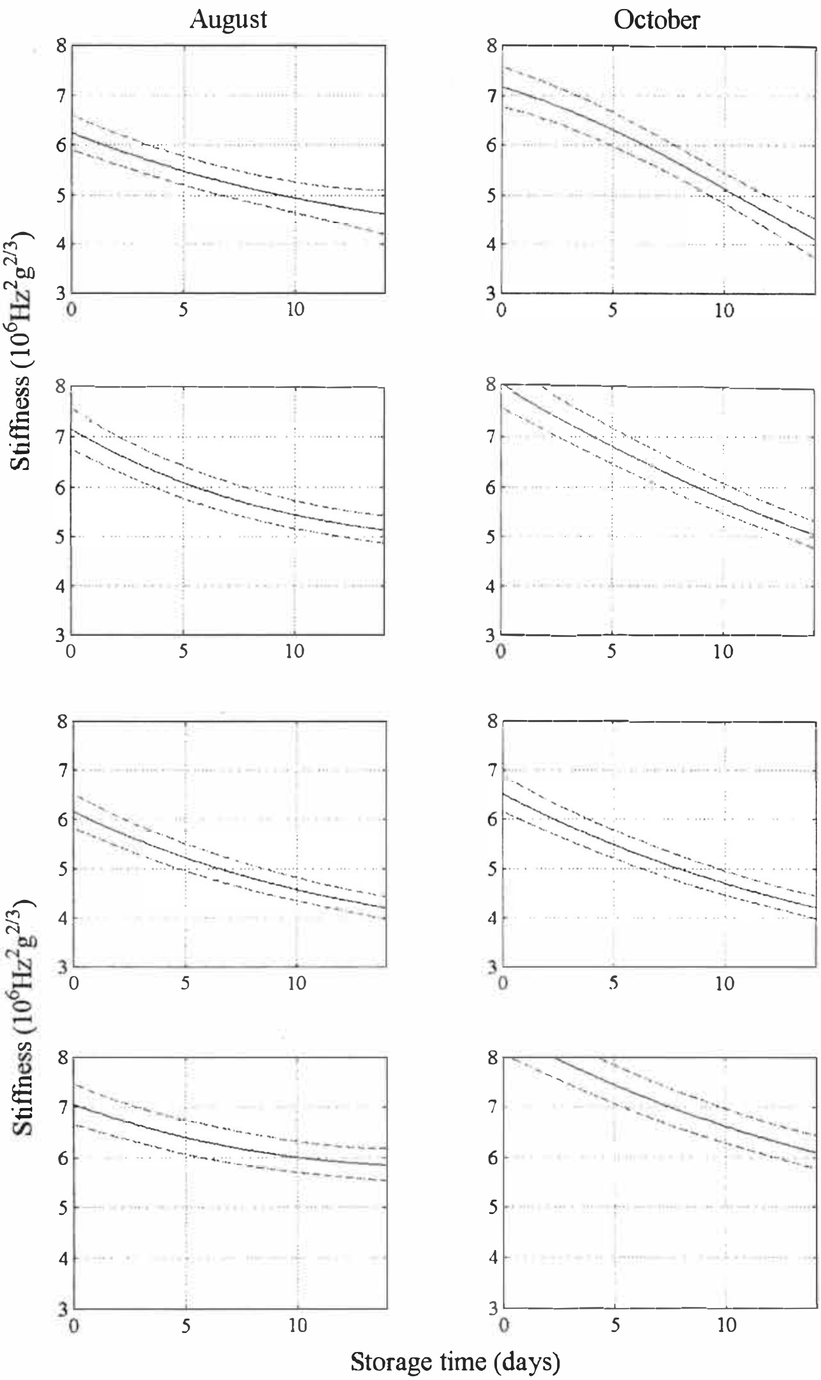

Fig. 4 *Modeled tomato stiffness as function of storage time, together with 95 % confidence bands for selected cultivars. (A) BS9445; (B) DRW5736; (C) DRW6340 and (D) DRW6391*

4. Conclusions

A non destructive sensor, based on the acoustic impulse response, was used to assess fruit quality. This type of sensor has proven their merit in laboratory scale experiments, but general acceptance is not yet fully reached, due to people being used to the older reference methods, and the difference in units and scales of such new devices.

It was shown that such an acoustic impulse response sensor is capable of detecting internal disorders in apples, while the classical MT firmness does not. This is probably due to the fact that the outer pericarp of the fruit, for which the MT gives information, remains undamaged, while the acoustic impulse response sensor provides an overall quality score – it is a global test.

The possibility non destructive sensors offer towards assessing a single fruit's quality repeatedly was discussed, together with the related data analysis issues. A novel statistical approach ('mixed models') to model such repeated quality measures was proposed using a practical example in which the firmness change of different tomato cultivars was considered. This type of model allowed quantifying different sources of variance, such as variance within a tomato cultivar and within a tomato, and how those sources of variance changed during storage.

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Itzhak Shmulevich*

Mechanical techniques for non-destructive sorting of agricultural products

1. INTRODUCTION

High-value fresh agricultural products, particularly for export, must be carefully handled and sorted in order to meet quality standards and customer demand. Many methods are available for quality detection and sorting according to internal and external fruit properties and defects. According to Mohsenin (1986), texture, together with appearance and flavor, are three sets of qualities, which govern the acceptability of fruit and vegetables by the consumer. In recent years, the demand for higher quality fruits and vegetables has led researchers to develop new technologies in order to improve the quality of products in the market. A major contribution to this goal has come from the application of developments in high-tech areas such as electronics, computers, sensors, materials, etc. Researchers are using the technology available to quantitatively define texture, appearance and flavor. Texture can be defined by subjective terms such as: hardness, softness, brittleness, ripeness, toughness, chewiness, smoothness, crispness, oiliness, springiness or firmness. It can also be defined objectively using physical terminology from continuum mechanics such as: elasticity, plasticity, viscoelasticity, or viscosity. This may be the reason that researchers define textural quality in different ways. One may refer to the textural quality, «firmness»; another may use the terminology «modulus of elasticity», while yet another may grade firmness indirectly by measuring chemical bonds. The absence of one quantitative definition for textural quality has resulted in different understanding of how to define texture and what is so-called "firmness". Nowadays, because of the dif-

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ferent firmness definitions, it is difficult to change the standards of quality used and to switch from destructive to non-destructive methods. One well-known example is the hopeless attempt of replacing the destructive Magness-Taylor (MT) pressure tester by one of the non-destructive techniques. It is obvious that these two types of techniques measure different physical properties and therefore, cannot present firmness using the same unit scale. As a result, numerous researchers have correlated the performance of their measuring technology with Magness-Taylor measurements, while others have concentrated on the advantages of newer, non-destructive technology. Using non-destructive techniques, one can inspect the same fruit throughout its ripening process to determine the fruit's optimum post-harvest treatment. In 1992 the Washington State Tree Fruit Research Commission (WSTFRC) asked for a sensing nondestructive technology to replace MT. According to WSTFRC the technology needed to meet three criteria: 1. To estimate MT values to within 1 lb in the critical regions of 8 to 14 lb (MT scale); 2. Did the sensor bruise any apples (even those below 10 lb MT)?; 3. Could the sensor be integrated into typical packing line systems? According to Pitts et al. (1997) none of the five tested sensors met the three WSTFRC criteria. Knowing that the MT destructive test depends on a fruit's size and its value varied much around the fruit perimeter, the question still remains: Can MT be the reference test for defining fruit texture? The industry is searching for a non-destructive test method. Other destructive tests such as a standard ASAE S36.4 DEC00 "Compression test of food materials of convex shape" using a parallel plate or cylindrical or ring sampling are also not realistic.

In recent years, several reviews have been published by Chen and Sun (1991), Sarig (1991), Pitts et al. (1993) and Abbott et al. (1997) on subjects directly and indirectly related to nondestructive firmness measurements. The need for quality detection by firmness technology has encouraged the scientific community to conduct conferences and workshops. Important developments over ten years have been published in the proceedings of conferences held by Brown and Sarig (1993), NRAES-97 (Orlando, USA, 1997), Shmulevich et al. (1997) and during special sessions of scientific associations and international conferences.

Major efforts have been directed towards dynamic quality detection by determining fruit response to force, impact force, forced vibrations, mechanical or sonic impulse, and ultrasonic testing techniques, as well as to indirect measurement systems. A summary of the findings applying to these methods will be presented. The objective of this work is to review the non-destructive techniques available to measure the textural quality known as firmness mainly by mechanical devices. The review will cover several promising techniques for adapting firmness measurement to the on-line sorting of fruit and vegetables.

The principles and important findings using those sensing means will be summarized and discussed with the aim of each of those methods to meet the challenge of a fast and cheap on-line nondestructive sorting firmness system.

The achievements of the mechanical means to sort according to fruit and vegetable firmness will be demonstrated by a comparison study between two quality nondestructive dynamic test methods, low-mass impact and acoustic response. The two leading nondestructive methods: fruit response to impact and acoustic detection, were compared with destructive parallel plates compression and penetration tests (Magness-Taylor) to evaluate the firmness of several fruits and vegetables.

2. MECHANICAL MEANS TO ASSESS FIRMNESS

2.1. *Quality detection by fruit response to force*

Several portable devices were developed by researchers such as Bellon et al. (1993) and Fekete (1993), to detect the force and deformation of fruit (about 0.3-0.9 mm). The researchers claim non-destructive operation as a result of using sensitive sensors. A high correlation to destructive tests was reported. Mizrach et al. (1992) developed a "mechanical thumb" to measure the force deformation of a peel using a spring-loaded device which was constructed on a flexible beam instrumented by strain-gages to measure the beam's deflection. Good results were reported in sorting tomatoes and Shamouti oranges. Mehlschau et al. (1981) developed a firmness deformeter using two steel balls for peaches. A similar method was presented by Flitsanov and Shmulevich (2001) for mangos.

2.2. *Quality detection by impact force*

2.2.1. Dropping the fruit on a force transducer

One technique for the firmness evaluation of fruits and vegetables was to drop the product on a force transducer. Among the first investigations on impact was the work of Finney et al. (1975), who recorded force versus displacement of a pendulum impacting a fruit. No practical conclusions were drawn, however. De Baerdemaeker et al. (1982) suggested determination of firmness according to impact force on apples that were dropped onto a force transducer. The frequency response of the impact was obtained via FFT. Several signal measurements were examined, among them the amplitude of the response at a predetermined frequency, e.g., F250 at 250 Hz, and the frequency at which a response is 20 dB lower than at 0 Hz, w(-20). The results were compared to those of MT and standard compression tests. Similar experiments were conducted on blueberries by Rohrbach et al. (1982). The results were compared to impact model results that were developed by Franke and Rohrbach (1981). An impact firmness index, $C_2 = F_p/T_p^2$, was calculated according to the time domain impact response, where F_p is the maximum force and T_p is the time from the beginning of impact until its maximum. Results indicated that this firmness index is not appropriate for blueberries, although it was later proven to be more appropriate for some other fruit varieties. Delwiche (1987) and Delwiche et al. (1987) found good correlation between two impact indices and results from MT and standard compression tests. The first impact index was defined as $C_1 = Fp/Tp$ and the second was C_2, as defined above. Correlation coefficients between the impact parameters and fruit characteristics were in the range of R=0.8. A prototype of a sorting unit, based on the impact firmness index C_2, was developed and tested by Delwiche et al. (1989). The fruit, which was discharged from a conveyor-belt, hit a rigid piezoelectric force transducer. An on-line computer analyzed the measured impact force and, using a pneumatic device, sorted the fruit into three groups - hard, firm, and soft. Thai (1995) presented preliminary tests of a Soft Transducer Tactile Sensor (STTS). The sensor is a 1 mm thick, resilient foam that changes its electrical resistance when mechanically deformed. Upon impact, the STTS senses changes in volume as opposed to changes in force, as in piezoelectric transducers. The time derivative of the measured signal is used to calculate an apparent coefficient of restitution. This value was found to be independent of drop height and mass of the fruit. The findings can be further explored for various fruits and compared to destructive tests. Schaare and McGlone (1997) reported on a SoftSort firmness sensing assembly that is based on measuring the dwell time, which is the half-height width of the force/time peak measured during an impact. The method was used to detect kiwifruit firmness by four sensor units made of piezo film sensor under an aluminum and rubber pad. The sensor units were concave in shape. Good sorting efficiency was reported for kiwifruit as compared to hand grading.

2.2.2. Impacting the fruit with a sensing element

Another impact technique commonly used is to tap the fruit with a medium or small impact device (low mass impact). Hung and Prussia (1995) presented a non-destructive Laser-puff detector to measure the firmness of various foods. The excitation of the food was performed by a short puff of pressurized air, which could be regulated to a certain degree according to the firmness scale of each product. A laser displacement sensor measured the deflected surface of the fruit. The Laser-puff values correlated well (R^2=0.78) with the destructive measurements in peaches. Delwiche and Sarig (1991) developed a firmness sensor of 63 g to impact the fruit. The acceleration of the mass gave a measure of the impact force that was analyzed to obtain the impact parameters C_1 and C_2. These parameters were normalized by the dropping height - h. The correlation obtained between C_2, C_2/h and standard compression tests were higher for peaches (R = 0.80), lower for pears (R = 0.68) and very low for Red Delicious apples (R = 0.53). Similar results were obtained by Ruiz-Altisent et al. (1993) for pears, avocados and apples. Chen and Tjan (1996, 1998) introduced a new mechanical system (see Figure 1) for low-mass impact based on a swing-arm sensor. They reported good performance of the system when testing rubber balls, kiwifruit and peaches. Preliminary tests showed that the sensor could sense fruit firmness at a speed of 5 fruits per second. Ortiz-Canavate et al. (2001) adapted a modified version of the low-mass impact method for an experimental fruit packing line with an operation speed of 5 to 7 fruit/s. Golden Delicious apples and several peach varieties were tested dynamically by the system and by destructive compression and MT penetration tests. Several impact characteristics were compared with the destructive test results. The correlation coefficients between the impact parameter C_1, when compared with force/deformation slope and MT penetration force, was quite high in peaches (0.93 and 0.87, respectively) but much lower in Golden Delicious apples (0.74 and 0.43, respectively). The authors reported that values obtained by the impact tests were very sensitive to variations in fruit form, location and impact angle. This work was repeated and extended by Homer et al. (2002), with similar results. Medium to high correlation coefficients were obtained between the impact parameters F_p, C_1, etc. and the destructive tests of nectarines and peaches; much lower correlation coefficients of 0.55 to 0.64 were obtained for Starking Delicious apples. It was observed that better performance was achieved for softer fruits. The researches reported a series of difficulties associated with the swing-arm sensor and its high sensitivity to variations in fruit position and orientation in the conveying system.

According to the cited literature the impact techniques have reached good results in the firmness evaluation of peaches, pears and some tropical fruits, but less in apples. As mentioned by various authors, local variations in texture around the surface of the fruit limit the accuracy of firmness prediction by impact testing. This is an inherent disadvantage of the method since the impact force is a natural measure of the local properties of the impact zone, rather than overall properties of the intact fruit.

Greefa Ltd. Introduced an on-line non-destructive firmness detection system (Armstrong, 2001), the intelligent Firmness Detector (iFD) (Figure 2) which is placed the singulator. Firmness measurements are done via a sensor that travels with the fruit as it rotates on a singulator. According to Armstrong (2001) there are 30 sensors along each line. The sensors go round and round in a loop above the fruit. One sensor will drop down and attach itself to a fruit moving at the same speed as the belt speed while it takes its readings.

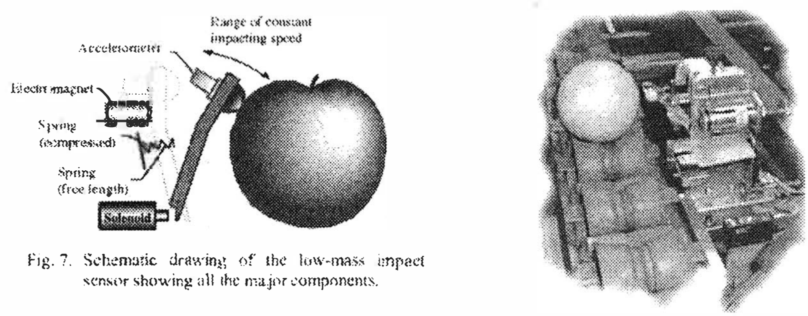


Fig. 1 *Low mass impact by Chen*

During the sorting process, a firmness sensor takes 9 to 20 measurements around the fruit. The system currently operates at speeds of 5-7 fruit per second depending on the fruit. According to the company the patented firmness detection system has been successfully applied in practice, for apples, avocados, mangoes, peaches and kiwifruit. Unfortunately, no quantitative data comparing the online system performances to destructive or sensorial tests have been reported.

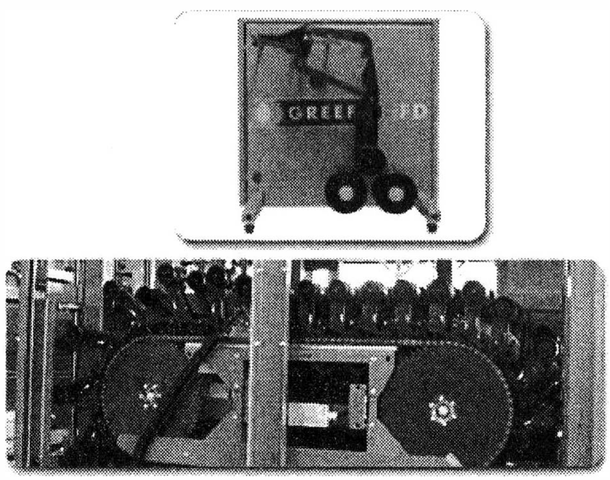


Fig. 2 *Intelligent Firmness Detector (iFD) by Greefa Ltd.*

Another company, Sinclair International Ltd., has developed the Sinclair IQ™ – Firmness Tester (SIQ-FT) that is based on a low-mass impact sensor (Howarth 2002) (see Figure 3). This on-line system measures firmness using a sensing element on the tip of a bellow. 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. Medium to high correlation coefficients were obtained with penetration tests for nectarines (0.85 to 0.95), plums (0.80), avocados (0.81 to 0.84) and kiwifruit (0.83 to 0.92). Good correlation between SIQ-FT and E modulus calculated from parallel plate were reported by Shmulevich et al. (2004). It was found that IQ correlated better to e-modulus compared to Cl and C2. The SIQ-FT on-line system currently operates at speeds of up to 10 fruit per second and makes four independent measurements that are combined to estimate the fruit firmness. These measurements are made on 4 different quadrants around the fruit surface.

In general the advantages of the impact method are its simplicity and speed. The disadvantage is mainly in the local detection; however, this disadvantage can be overcome by multi measurements around the fruit.

2.3. *Quality detection by fruit response to forced vibrations*

A vibration test is referred to as an experiment where a fruit is excited by a commercial vibrator on one side, while the response is measured by an accelerometer or a microphone attached to its opposite side. Usually, the response in time is transformed to give a frequency response in order to detect the resonant frequencies of the fruit. The resonant frequencies depend on the mechanical properties of the fruit and therefore can be used to characterize fruit firmness.

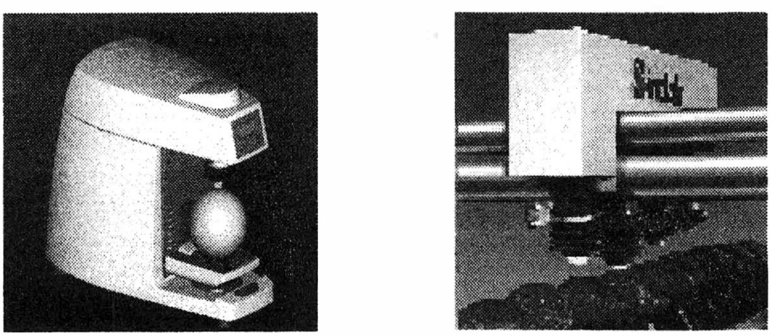


Fig. 3 *SIQ-FI system by Sinclair*

One of the first studies on the non-destructive evaluation of fruit quality factors and their dependence on mechanical properties was done by Finney (1967), who reported on a correlation between the extent of fruit ripeness in apples, pears and peaches and the Young's modulus of the fruits. The Young's modulus was calculated according to the resonant frequency of a fruit specimen, which was vibrated at frequencies ranging from 20 - 3000 Hz. The results showed a change in the modulus of elasticity within a range of 3% per day during the last two weeks of ripening. Similar results were reported for bananas by Finney et al. (1968). Finney and Norris (1968) found strong correlation between the Modulus of Elasticity of whole fruit and fruit specimens, and their resonant frequencies. Abbott et al. (1968) vibrated intact fruits, which were hung by their stems, and suggested a firmness index, $FI = m\,(f_{n=2})^2$; calculated according to the second resonant frequency of the vibrated fruit, $f_{n=2}$, and its mass, m. Utilizing a similar approach, Stephenson et al. (1973) and Peleg and Hinga (1989) reported good results in separating green from red tomatoes according to the difference in their frequency response. Peleg et al. (1990) reported good classification results of avocado based on the same measuring system but using four quantities of modal firmness indexes, which were calculated directly by measuring the input and output vibration signals. A prototype-sorting machine by firmness and vision was introduced by Peleg (see Figure 4).

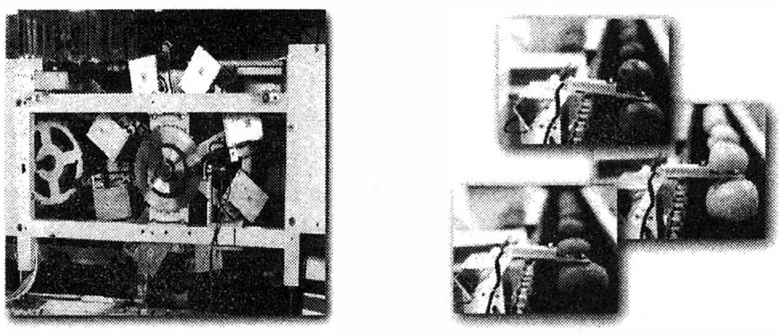


Fig. 4 *The Peleg Firmness Sorter (PFS)*

Abbott and Massie (1995) proposed a non-destructive dynamic force/deformation measurement for kiwifruit firmness using a force transducer and accelerometer on the head of an electrodynamic vibrator. Both transducers measured the input and output signals from the same side of the fruit. Technically, this arrangement is more convenient for on-line adaptation. From the dynamic force deformation frequency response, they calculated the ratio of the output to input at each frequency, to obtain the frequency response. Using the firmness index term, low correlation (R=0.6) was achieved between dynamic force versus deformation variables and the MT. Improvements on the correlation were achieved (R=0.8) by taking into account the two frequency ranges, using a multiple regression technique.

Cooke and Rand (1973) developed a mathematical model for investigating the dynamic response of fruit. The model was based on the classical theory of free vibrations of an elastic body. The mathematical model was used to calculate the free vibration modes of a spherical fruit composed of three layers, each having different elastic properties. The free vibrations of the sphere were divided into three basic classes: (1) spherical, breathing mode of vibrations, S_{0j}, for which the volume of the sphere changes while its shape remains unchanged, (2) torsional vibrations, T_{ij}, for which the volume and shape of the sphere remain unchanged while different parts of the sphere move relative to one another, and (3) mixed modes vibrations, S_{ij} ($i > 1$), for which both the volume and the shape of the sphere change. In addition, a correction of the firmness index, $FI = m^{2/3} (f_{n=2})^2$, was derived from this theoretical study and found to be independent of the fruit mass.

Yong and Bilanski (1979) measured the frequency response at the top and side of a fruit and derived the modal shapes of vibrations. The first resonance was found to be similar to a single degree of freedom system (SDOF), where most of the fruit may be considered as a solid mass. Only a thin layer, at the point where the fruit rests upon the vibrator, may be considered as a spring and dashpot. The second resonance was found to be a mixed mode of vibrations - S_{20} - that is called the oblate prolate mode. The higher resonance frequencies were assumed to be of the same type but have a higher order - S_{30}, S_{40}, etc. These conclusions were experimentally confirmed by Van Woensel et al. (1987, 1988).

Rosenfeld et al. (1991, 1993) developed a Boundary Element simulation, which extends the model of the elastic sphere of Cooke and Rand (1973). The simulation provided the acoustic response of a viscoelastic fruit, of arbitrary shape, that was excited at its bottom. The numerical simulation yielded the shapes of the first and second vibration modes, which were experimentally detected in previous work. The simulation also showed the dependence of the resonant frequencies on the viscoelastic properties of the fruit, as well as on its mass and fruit shape. The results corroborate the fact that it is possible to sort fruit for firmness when the mass and the resonant frequency of the fruit are known. Chen and De Baerdemaeker (1993), Chen H. et al. (1996) and Jancsok et al. (2001) analyzed the modal shapes of fruits using a finite element model and examined the effect of fruit shape on the vibration modes. They concluded that the fruit shape in irregular fruits like "Conference" pears had a significant influence on the resonant frequencies. Kimmel et al. (1992) used a lumped parameter model, based on a multi degree-of-freedom system (MDFS), and verified the modal shapes of fruits.

From the studies presented, it can be concluded that the forced vibrations technique is feasible as a method for detecting degree of fruit ripeness. Nevertheless, these findings have not yet led to the construction of an on-line quality sorter, mainly because of problems associated with coupling the measuring device to each individual fruit.

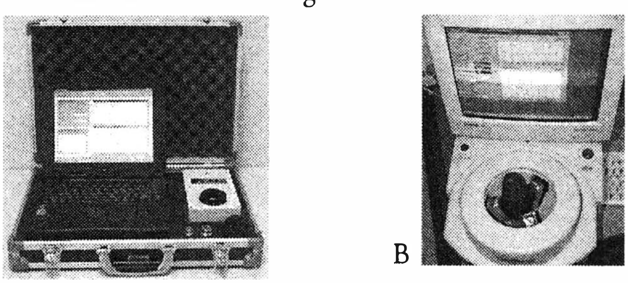
2.4. *Quality detection by a mechanical or sonic impulse*

An alternative method for evaluating textural quality via frequency response was suggested by Yamamoto et al. (1980, 1981). The fruit was placed on a rigid surface and hit by a pendulum. A microphone sensed the acoustic emission and the signal were analyzed using an FFT algorithm to extract the fruit's resonant frequencies. The researchers showed a significant correlation between the acoustic parameters of apples and their apparent Young's modulus, ultimate strength and firmness. The correlation for watermelons was poor. Abbott et al. (1968) indicated similar resonant frequencies for the same modes of vibration, which were excited by forced vibrations. The first mode from Abbott's vibration test does not appear in Yamamoto's study, since it is a forced vibration mode, as previously explained. To prove this hypothesis Van Woensel et al. (1988) used the following two experimental set-ups to measure the resonant frequencies and damping ratios: (1) forced vibrations by the standard vibrating method, and (2) free vibrations by a small pendulum which hit the fruit that was hung by its stem. They found that the first resonance measured by the forced vibrations setup was not detected by the free vibrations setup, which only measured natural frequencies. The frequencies and damping ratios of the higher modes of vibration, measured by the two experimental setups, were very close to each other. These results confirmed the findings of Yong and Bilanski (1979), that the first resonance is of an SDOF type, and the higher resonances are of the mixed modes. Armstrong et al. (1990, 1992) caused vibrations by striking the apple with a ball of wax. Young's modulus, calculated from the acoustic response, highly correlated with that measured in the compression tests of specimens taken from the same fruit. Poor correlation was found with the results of a standard MT test. Good repeatability results were obtained from impulses applied at the equator of the apple, while those applied at the stem or blossom ends and detected at the equator did not show good results. Chen, P. et al. (1992) reported good correlation of the first two resonant frequencies between acoustic sensing and human auditory sensing. In the experiments, several apple varieties were struck mechanically while a microphone detected fruit response. Significant differences were not found among sound signals obtained at different locations tested around the fruit. Chen, H. et al. (1992) tested apples and concluded that the acoustic impulse response method appears to be more efficient and accurate than random vibration methods, and the instrument, more practical to use. Sugiyama et al. (1997) developed a portable firmness tester for melons. The device was based on detecting the response of a melon, by two microphones, resulting from mechanical impulse excitation. Correlation of about R=0.943 was reported between the transmission velocity measured by the microphones and the apparent elasticity of the melons, measured destructively. Farabee and Stone (1991) developed a nondestructive firmness tester to measure the maturity of watermelon using sonic impulse. The probe is a closed end, Plexiglas cylinder approximately 5 cm in diameter and 15 cm long. A thin, disk shaped ceramic piezoelectric element, bonded to a similar sized thin brass disk, was mounted at the end of the cylinder in contact with the melon. A solenoid, inside the cylinder, was used to deliver a mechanical impulse to the flat face of the piezo ceramic. The impulse is transferred through the ceramic to the watermelon. The resulting vibration of the melon, due to the impulse, drives the piezo element. The signal from the element was amplified and filtered through a fourth order low-pass active filter before digitization by the data acquisition unit. This equipment was used by Armstrong et al. (1997) in recent research to detect the internal damage of watermelons and by Stone et al. (1996) to detect watermelon maturity in the field.

A piezoelectric-film based measurement system – Firmalon^{TM} – (reported by Shmulevich et al., 1995, 1996) was constructed by Eshet Eilon Ltd. (Figure 5B). The system includes a force transducer to detect the fruit's mass, an instrumented fruit-bed with three equally spaced piezoelectric sensors, and three electro-mechanical impulse hammers. The piezoelectric sensors are composed of a polyvinylidene fluoride film bonded to a soft polyethylene-foam padding, to enable free vibrations of the fruit. The impulse devices, consisting of a push-type solenoid and a pendulum, are located opposite the piezoelectric-film sensors. A data acquisition computer program was used to control the test operations, to select the resonant frequencies and to calculate the acoustic parameters of the fruit. The acoustic parameters were: the natural frequency of the fruit; damping ratio and the centeroid of the frequency response (Galili et al., 1996). The spectral analysis of the signal follows similar procedures as for the general vibration testing of structures. However, for automated, on-line firmness testing of fruit, the analysis methods used should ensure that the first mode of vibration is detected even in the case of non-uniform and irregularly shaped fruit. An automated search algorithm was used to identify the first frequency of fruit response to impulse excitation. The conventional expression of FI = $f^2 m^{2/3}$ was employed for firmness calculation, even though the fruits were not always spherical. Future work needs to improve the spherical model assumption.

The research group of K.U. Leuven led by Prof. De Baerdemaeker developed an acoustic firmness tester based on a microphone. Recently, AWETA Ltd. Offered a bench top device: AFS^{TM}, which enables the nondestructive measurement of fruits and vegetables (Figure 5A). A study reported by Galili and De Baerdemaeker (1996) demonstrated that the acoustic method by microphone and piezoelectric-film measured alike. Unfortunately, the acoustic method did not materialize to an on line system. The company launched recently an on-line firmness detection system, which can be incorporated into existing lines (Figure 6) currently measuring six fruits per second.

Thus, several parameters are available for fruit quality evaluation through mechanical and acoustic excitation. The most promising quality factor seems to be the resonant firmness index, calculated through impulse excitation. Analysis of the response to a mechanical impulse is a feasible method to obtain the firmness index, and can be adapted more easily to sorting machines. However, as stated by Pitts et al. (1993), judging the effectiveness of a new sensor system for fruits can be a very difficult task; besides the variation capability in the sensor system and the sensor's correlation to firmness, there is variation in firmness around the fruit as fruit size changes.



A B

Fig. 5 *Acoustic firmness tests AFS^{TM} by AWETA (A) and Firmalon ^{TM} by Eshet Eilon (B)*

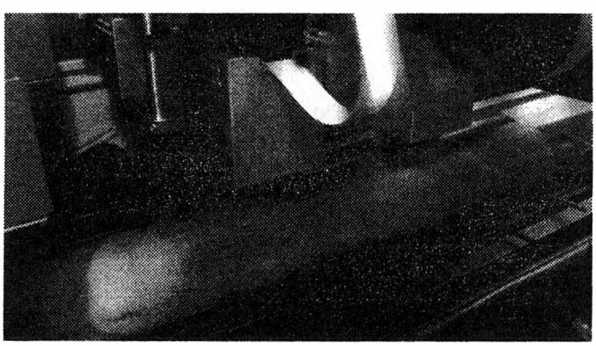


Fig. 6 *Acoustic online firmness tests AFS^{TM} by AWETA (Source AWETA)*

These investigations of the response of fruit to a mechanical or sonic impulse indicate that this method is reliable and easy to apply. However, the excitation method and measuring techniques must be further developed and adapted to actual conditions in the sorting process.

2.5. *Determining fruit properties by ultrasonic techniques*

Ultrasonic diagnostic testing is a well-established, non-destructive technique used in medical and industrial applications. In industry, these techniques are used to detect internal defects such as air pockets and cracks in welding and casting, whereas in medicine they are used to determine normal and abnormal tissues, as well as the internal structure of organs in the human body. The frequency of ultrasonic waves is a very important factor in fruit penetration, since the attenuation of high frequency waves in fruit tissue is very high. Sarker and Wolfe (1983) found high attenuation coefficients of ultrasonic waves at the frequency range of 0.5 - 1 MHz in tissues of potatoes, cantaloupes and apples, due to the porous nature of these tissues. The spectral analysis of ultrasonic acoustic waves was investigated by Upchurch et al. (1985,1987), for the purpose of detecting damage in apple tissue. It was observed that undamaged tissues contained a larger percentage of air space than that of damaged tissues. However, due to the high acoustic impedance and attenuation coefficient of apple tissue, this change in tissue construction could not be consistently detected by using the ultrasonic technique. Mizrach et al. (1991, 1996) studied acoustic, mechanical and quality parameters of melons and avocado using a 50 kHz transducer. The attenuation signal correlated well with firmness in avocados (see Figure 7). Low correlation was found for Galia melons.

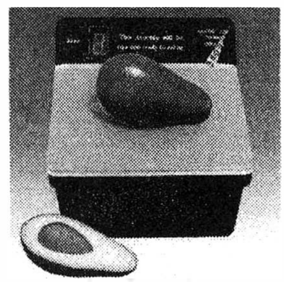


Fig. 7 *Estimating Avocado ripeness by ultrasonic device (Source Mizrach)*

The literature survey indicates that ultrasonic techniques can be used to detect only some local properties and specific defects in selected products. Yet, the commercially available, low frequency ultrasonic transducers are suited for laboratory use only, because of their large dimensions, rigid construction, and poor coupling features. The success of firmness measurement is limited to certain fruits and found not suitable for detecting apple firmness due to their high void ratio.

2.6. *Indirect firmness measurements*

Currently several researchers (such as Lu et al. 2004) and commercially companies such as: Unitec-Italy, TTL-New Zealand, Color-Vision-Australia, F5 by Sacmi-Italy and others are presenting non-destructive internal quality sorting systems incorporating Near Infra Red Technology and Hyperspectral Imaging. The researchers a companies climes high correlation to firmness. These indirect measurements of transmitted or reflecting light in NIR range correlated well with fruit maturity stage and can be considering as an added data to the sorting decision. Still theses methods are more sensitive to fruit temperature, needs to be calibrated for each fruit type.

Other nondestructive techniques such as Nuclear Magnetic Resonance-NMR or MRI and Fluorescence are still in R&D stages.

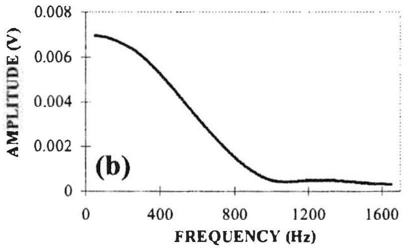
3. EXAMPLES OF THE SYSTEM PERFORMANCES IN VARIOUS FRUITS

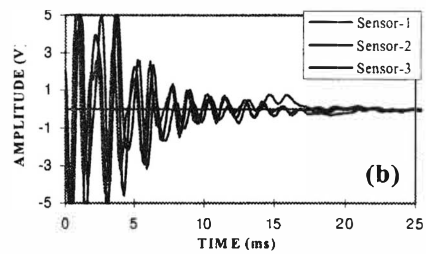
The methods used by Shmulevich et al. (1996, 2003,2004) and Galili et al. (1998) can demonstrate the acoustic and low mass impact non-destructive technique on apples, pears, tomatoes, mangoes, avocados and melons. The data presented below shows the potential of non-destructive measurement as well as the difficulties due to the large variation in size of the fruits. Results from the non-destructive tests are also compared to destructive measurements.

3.1. *Typical acoustic signals*

Typical acoustic signals of Jonagold apples acquired by the Firmalon are shown in Figure 8 (Galili and De Baerdemaeker, 1996). In Figure 8(a) the input signal of one excitation is presented. Figures 8(b),(c) show the output in time and frequency domain, respectively, measured by three sensors.

Typical results of a melon's response in the time and frequency domains are presented in Figure 9. In the frequency domain, the signals were shifted upward by 0.1 normalized units in order to show their behavior more clearly. It can be concluded that three sensors are measuring the same frequency response, independent of sensor location. For Galia melons, at least five natural resonant frequencies were detected in the frequency spectrum whereas only one or two major frequencies were detected in apples.





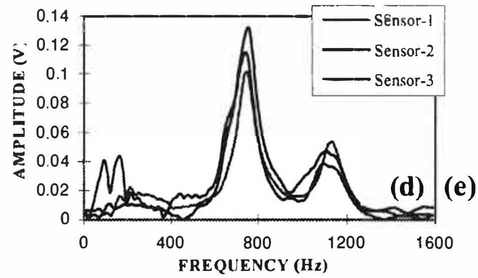


Fig. 8 *Typical acoustic signals of a Jonagold apple (a) is the input signal, (b) the time domain signal and (c) the frequency domain signal*

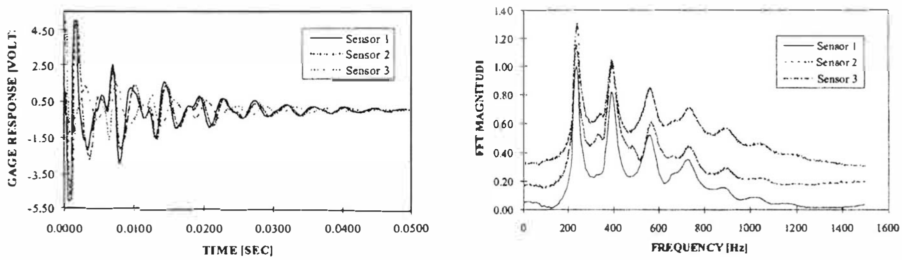


Fig. 9 *Typical signals for a melon, in the time and frequency domains*

3.2. *Acoustic vs. destructive tests of apples*

A comparison between the MT and FI test results in Golden Delicious apples is presented in Figure 10. No correlation was found between the MT and FI (Figure 10a). In addition, a low correlation was found between the two MT measurements taken from opposite sides of the same apple (not shown in the figure). Figure 10b shows the average FI, the average MT and the standard deviation for each day of measurement versus storage time. Figure 10b demonstrates why there is no correlation between MT and FI; the MT of the different fruits does not change much during the thirty days of shelf life, while the FI values decrease with time. It was concluded that, compared to the MT, FI is much more sensitive to the ripening process of apples during shelf life. Similar findings were reported by Galili et al. (1996) and Pitts et al. (1997). These findings emphasize the need to replace the MT test with one of the nondestructive methods.

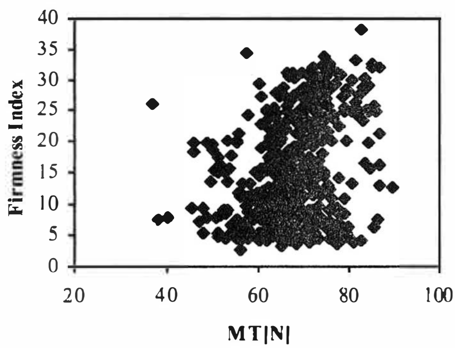


Fig. 10a *Firmness Index vs. MT for 500 Golden Delicious apples*

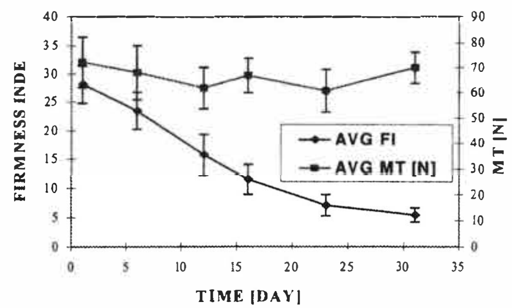


Fig. 10b *Average Firmness Index and average MT vs. time*

3.3. *Comparison between acoustic and low mass impact techniques*

In general, the low mass impact technique performed similar to the acoustic technique as was demonstrated by Shmulevich et al. (2003,2004) in apples, avocados, mangos, melons and other fruits and vegetables. In soft fruits, the low mass impact technique measured the firmness better than the acoustic technique. The acoustic technique has some priority when compared to the low mass impact technique measuring hard fruits. The acoustic technique may also have an advantage in identifying internal damages and disorders in fruits. The presented conclusions are based on destructive reference fruit firmness studies, which calculated the value of the Apparent Modulus of Elasticity of the fruit according to the ASAE standard using the fruit's properties from a parallel plate loading test.

4. CONCLUSIONS AND FUTURE VIEW

The achievements in detecting firmness and the softening process of fruits and vegetables by mechanical non-destructive techniques are satisfactory. The acoustic or low mass impact method, described here, needs to encourage researchers to improve the techniques to be used commercially. They need to be developed further mainly from the reliability point of view. The leading promising techniques to commercially detect fruit firmness are: low mass impact, acoustic and fast indirect detection mainly by NIR spectroscopy. Although researchers addressed the physical phenomena of the sensing methods long ago, it is still a hard and slow process to convince the food industry to use the technologies, mainly because of conservative thinking and the fact that quality cannot be measured by only one quality attribute. The high variability of fruit change, due to its natural material, needs to be addressed more if those methods will be developed from laboratory bench-top devices to real online sorting machines. Still, for each fruit and vegetable, boundaries need to be found in order to explore the optimum sorting process. Special high quality items need to be identified and to comply with consumer preferences.

New sensorial techniques, fast data analyzing and new classification tools need to be applied in the near future for the sorting process. Several other quality measurement attributes need to be coupled with firmness sensing using fusion technologies. More effort needs to be put into improving the method's reliability in uncontrolled environment conditions.

Development of several other applications based on mechanical principles can be made. One application is a fruit-ripening sensor, which detects the ripening process of several representative fruits in CA storage or during the artificial ripening process (Shmulevich et al., 2003). Knowledge from those measurements can contribute to management decisions. The second application can be a device to detect the changes in fruit maturity while the fruit is still in the field. These applications are part of the "speaking plant" concept, which uses new sensors to provide information on the current fruit condition.

The achievements of the development nondestructive methods need to be urgently addressed in new standards to benefit customers' food distributors and industry.

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Riccardo Guidetti*

Optical systems to evaluate the quality of products

1. INTRODUCTION

The Agricultural Engineering Institute of the University of Milan started its experiences in the application of not destructive technologies for the evaluation of product from the 1993 when was constituted the Hi Tech Group under the leadership of professor Bodria. The principal activity is in the field of the analysis of the maturity stages and quality of agricultural products with some experiences also in the not destructive evaluations of the food products.

These researches are conducted using, especially, optical methods applying these techniques for punctual measurements and for image analysis.

2. THE FRUIT AND VEGETABLES CHARACTERIZATION

During ripening a fruit or vegetable undergoes several concurrent and sequential biochemical processes that deeply transform its properties. These changes affect the quality attributes in terms of: texture and firmness (due to solubilization of pectin); flavour (due to: starch conversion into sugars; changes in organic acid content; production of aromatic volatiles); colour appearance (due to: chlorophyll degradation in the skin; synthesis and/or unmasking of carotenoids and anthocyanins).

These biological phenomenon are the basis of all the researches which use

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different physical approaches with the common aim to characterised the agricultural products in terms of quality or ripeness with non destructive methods.

The validation of these systems is obtained comparing the data from the experimental set-ups with those from conventional destructive methods (firmness, content of soluble solids, chlorophyll content) or from colour measurements using a colorimeter.

3. Punctual measurements

The punctual measurements permit to characterised the products only in a particularly region giving very interesting data about the sugar content and the maturity stage.

3.1. *Dual-band reflectance measurements*

The aim of this experimentation is to design a device for in field measurements so that the operator could follow the ripeness of fruit again in the orchard.

The experimental set-up for the pointwise measurement (fig. 1) use the red and near-infrared bands and consist of:

- a 10 mW laser diode which emits monochromatic light at a wavelength of 675 nm and a pair of LEDs emitting at 800 nm, which sequentially illuminate the portion of the fruit being analysed;
- two photodiodes, integrated into the system, which collect and measure the light reflected by the fruit when illuminated by the two types of sources;
- one computer for the acquisition and storage of the measured data.

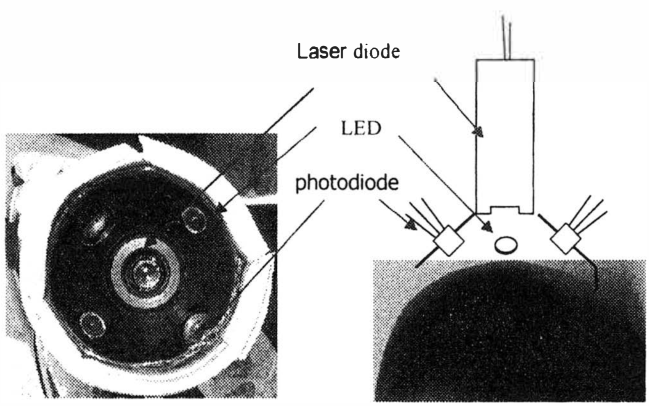
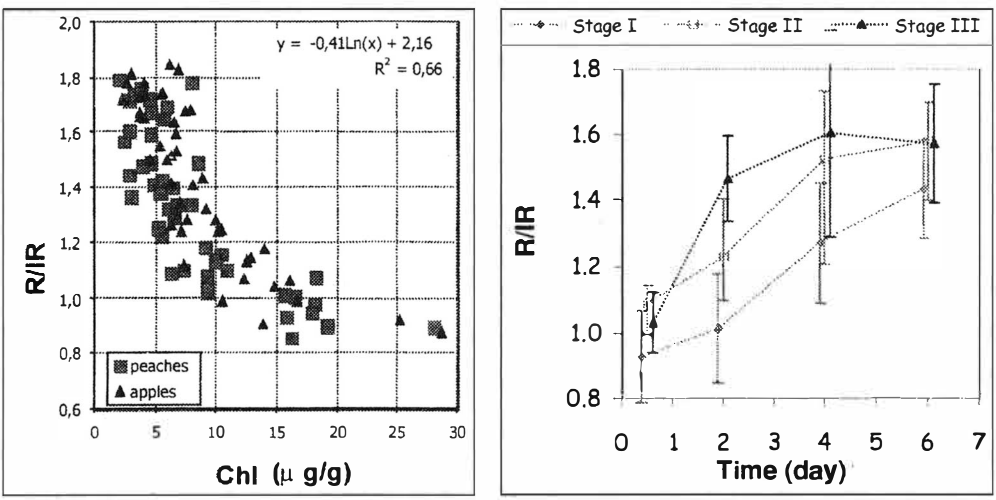


Fig. 1 *System for punctual two bands refletance*

The testing of the method involved resting the probe directly on the equatorial region of the fruit, and then manually triggering the PC to acquire the reflectance value obtained under illumination with the laser and the LEDs.

The tests with the set-up for pointwise reflectance measurement, conducted using peaches (*cv Summer Rich*), nectarines (*cv Big Top*) and apples (*cv Red Delicious)*, led to the determination of an *R/IR* index, which is the ratio between reflectance in the red band at 675 nm (*R*) and reflectance in the infrared band at 800 nm (*IR*). Because this index is a ratio between two measured values, it is unaffected by the geometry of the reflectance measurement. In particular, this index was found to successfully predict the chlorophyll content with a good accuracy (R^2 = 0.6 – 0.7 depending on the cultivar analysed, fig.2a). Some of



a) b)

Fig. 2 *a) R/IR index vs chlorophyll content; b) behaviour of R/IR index during post-harvest days*

the tests were carried out in such a way as to follow the development of fruit harvested at different stages of maturity and opportunely graded by experts. Using the reflectance measurements and the *R/IR* index, it was possible to track the ripening of the fruits even in the absence of significant variations in colour (fig.2b). The test showed how the slope of the fruit maturation curve changes as a function of the initial state: the ripest fruits have a steeper slope at the beginning, which indicates rapid degradation of the chlorophyll; the more unripe fruits, on the other hand, have a curve with a lower slope, reflecting slower degradation of the chlorophyll. In both cases, however, the same ratio is reached (*R/IR* > 1.4) at the end of the monitored period (6 days), indicating that maturation is complete.

3.2. *NIR techniques*

The spectral data are one of the most important source of information to know the organoleptic properties of fruit and vegetables. With this aims, an experimental device, based on a VIS-NIR spectrometer, was designed and realised to collect the spectrum without any part in contact with the products and so to work on line, where the products have to have particularly orientation.

The aim of the research is to develop some spectral algorithms to evaluate the sugar content with a limited number of wavelengths. In some cases is studied the possibility of predicting also the firmness and the acidity, but the experimental phases are going on again.

The device used for these studies is constituted by:

- a dark chamber, to avoid the interference of the external light, with three halogen lamps powered by 50 W, situated in the same plan in an orthogonal way, to illuminate three faces of the products; in the free late (the fourth of the chamber) there is the optical fibre to collect the light through the fruit and transferred it to the spectrometer;
- a spectrometer, working in the interval between 550 and 1100 nm, which need to acquire the spectrum of a time of 150 ms;
- a PC, to acquire and stored the spectrums and to menage the spectrometer.

The spectrums are transformed to eliminate the disturbs of the measurements and avoid the not significant informations.

The spectral data and the reference values obtained by the classical destructive methods, are inserted in the data-table of the statistical programme Unscrambler to elaborate the calibration models, with the use of the second derivative of the transmittance value, like independent data, in the regression and the destructive value, like dependent data. The derivative spectrum conserved the peak' positions, removing the additive effects in the spectra, and permit to underline the variation of the spectra data due to the soluble solid content of the fruit.

The regression, between spectra and organoleptic data, is calculated with the techniques of the Partial Last Squares (PLS), a very circulated method for the statistical multivariate analysis of a high number of independent variables. The equation is, then, applied to predict the values on a set of fruit which aren't used in the calibration phase.

Besides, the most interesting intervals of wavelengths for the calibrations in the PLS, are used for another regression: the multilinear regression (MLR). With this algorithm is investigated the possibilities to use a simpler model, but always reliability, than the one by the PLS.

The experimentation was conducted on kiwi, apples and oranges. In every case the results show a good correlation between the Brix grade obtained with the destructive methods and the predictions by NIR.

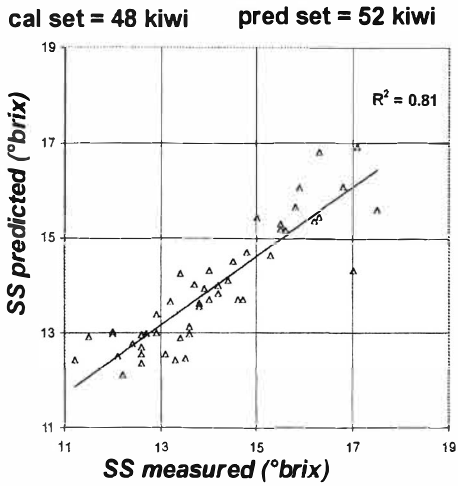


Fig. 3 *Predicted SS vs measured SS for Kiwi (cv Hayward)*

Kiwi (cv Hayward)

The PLS model obtained good correlation (R^2 = 0,86) between the destructive values and the predicted ones, while the Standard Error of Calibration (SEC) is about 0,5 °Brix. In prediction, with another set of fruit, there is always a discrete correlation (R^2 = 0,53) with a Standard Error of Prediction (SEP) of 1,0 °Brix. The MLR obtained comparable results: in calibration the correlation was good with a coefficient of R^2 = 0,86 and a SEC of 0,6°Brix, while in prediction the coefficients became 0,63 and 0,9 °Brix.

Orange (cv Navel and Tarocco)

The study was developed in two years using *cv Navel* and *cv Tarocco*. The model is the result of the joint of both the data. The PLS model obtained, in calibration, a good correlation (R^2 = 0,88) and a SEC of 0,48° Brix, while in prediction the results are R^2 = 0,58 and SEP = 0,65 ° Brix. Also MLR analysis was conducted: in calibration it was obtained R^2 = 0,87 and SEC = 0,50 while during the prediction phase R^2 = 0,53 and SEP = 0,73°Brix.

The study was extended to the prediction of the colour of the juice (fig.4): the PLS prediction obtained a R^2 = 0,79 and a SEP = 0,41 showing like the spectrum analysis contained also this information.

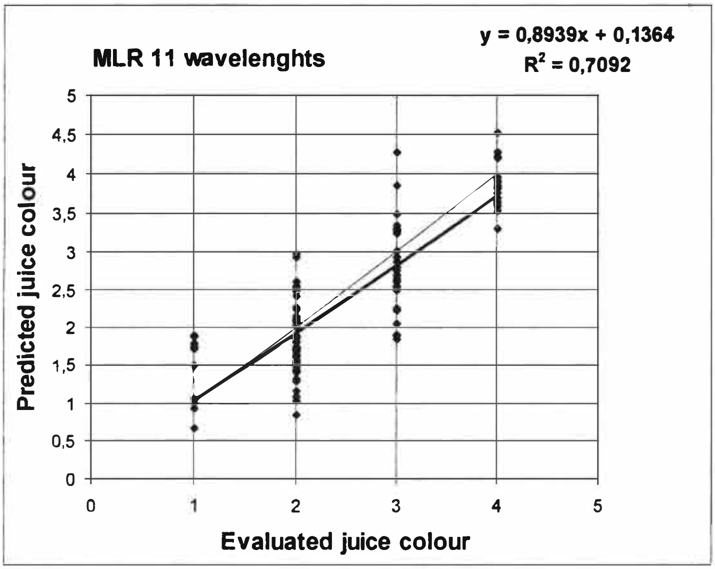


Fig. 4 *Predicted colour vs estimated colour for oranges juice (cv Navel and Tarocco)*

Apples

The study is working on to evaluate the influence of the position of the fruit respect the lights and the direction of the axis of the fruit. The first results, showed in the table 1 in term of predictions, display that the most interesting position in the dark chamber is with axis in the horizontal position with two lights (R^2 = 0,72, SEP = 0,65 ° Brix).

Table. 1 *Effect of the position of the apple on the R^2 and SEP during NIR prediction*

Apple position	R^2	*SEP*
Vertical, 3 lamps	0,407	0,89
Vertical, 2 lamps	0,302	0,94
Horizontal, 3 lamps	0,504	0,85
Horizontal, 2 lamps	0,722	0,65

3.3. *Strawberries brightness*

The strawberries are a very delicate and particular fruit so that it isn't used the recently indices for the agricultural products (colour, NIR analysis, ecc.) but the interest of the operators is about the brightness, because the fruit which have a surface particularly bright seem to have a longer shelf life.

The aim of this study is to design a simple device to evaluate the brightness of single strawberry. The experimental set is composed by:
- a light source constituted by a laser with a wavelength of 635 nm and an ocular that can open the pencil of light till 20 mm;
- a photodiode with a biconvex lens to focalise the reflected ray in the sensible part of the photodiode to have a better tension signal;
- two supporter arm (one for the laser and the other for the photodiode) mounted on a goniometer to have the exact incident and reflection angles;
- a vertical mobile plan to obtained the perfect condition of mirror reflection.

The experimentation of the set regarded about one thousand strawberries both fresh and refrigerated, which are correctly divided by experts in two classes where the level of quality are proportional to the level of brightness.

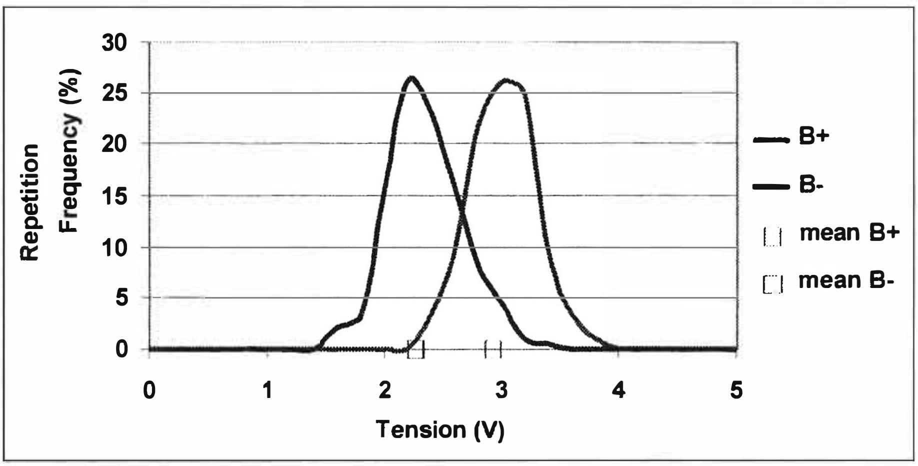


Fig. 5 *Identification of the two classes of strawberries: the more bright (B+) and the less one (B–)*

The results show that the device can distinguish the two classes (fig.5) giving to the more bright class the higher value of tension The differences between the medium value of the two classes is of 0,35 V for the fresh strawberries and 0,6 V for the refrigerated strawberries.

This results indicated like this method could be interesting both to develop a simple device and to suggest the possibilities to use also image analysis.

4. IMAGE ANALYSIS

The image analysis use cameras to detect the characterisation of the superficial level of the agricultural products. Using special filters it is possible to have also images from the not visible part of the spectrum, which can show particular properties of the fruit.

4.1. *Fluorescence images*

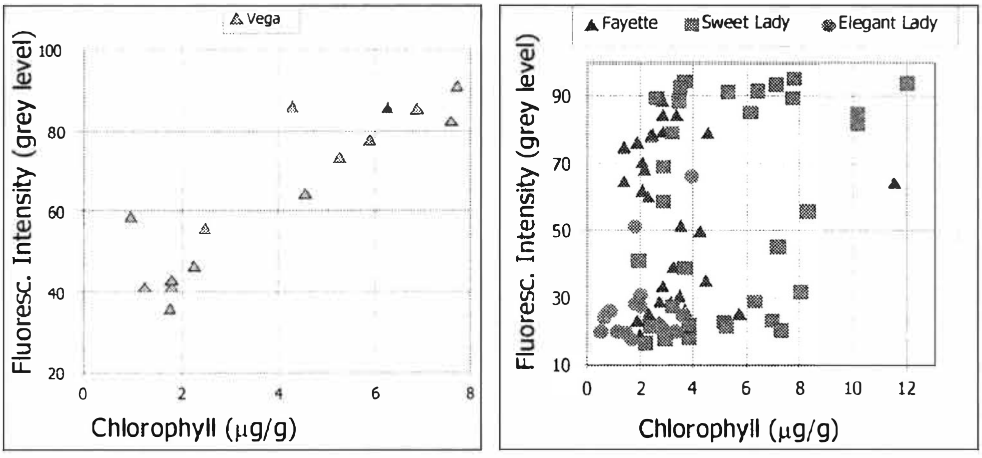
Among the various parameters that undergo measurable changes during the fruit maturation process, the degradation of chlorophyll - responsible for the loss of green colouring from the skin of many fruits - is an important element for characterising the stage of fruit maturity. What's more, the possibility of determining the chlorophyll content through fluorescence measurements makes this an extremely interesting index for determining the stage of maturity of the products.

The experimental set-up for the measurement of fluorescence consisted of the following elements:

- one dark chamber equipped with a light source for the excitation of fluorescence and with the various components assembled inside, including a height-adjustable support on which the sample fruit is placed;
- one CCD camera equipped with an RG-695 high-pass filter which transmits only radiation having wavelengths greater than 690 nm; this camera is connected to a frame grabber (Date Translation DT 3155) which digitises the images and stores them on the hard disk of the PC controller, ready for subsequent analysis by a special software program.

Two different systems were used for illuminating the fruit: one with a *blue light source*, consisting of two 600 W ULTRAMED mercury lamps for illuminating the fruit and a BG-40 low-pass filter that transmits only radiation having wavelengths of less than 600 nm, equipped with a manually operated diaphragm for controlling the exposure time of the fruit to the light beam; a second *red light* system in which an illuminator, consisting of a series of «ultra-bright» type LEDs mounted on a dome shaped support, emits red light at 650-680 nm.

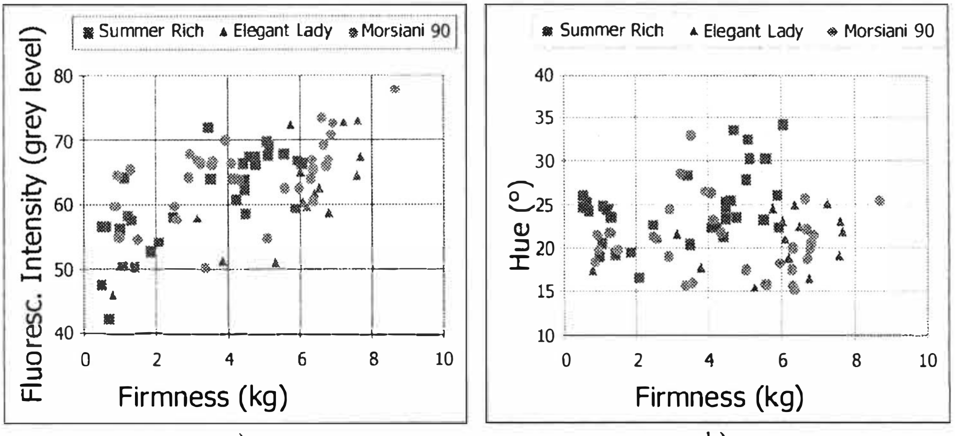
During the testing the fruit was placed inside the dark chamber and the resulting fluorescence image captured by the camera was analysed to quantify the pixel intensity (greyscale level) in the equatorial region of the fruit, which is the part that best indicates the stage of maturity. In particular, the system for fluorescence image analysis under blue light was tested on apricots (*cv San Castrese*) and apples (*cv Red delicious*), obtaining a good correlation with the sugar content and hardness values determined by destructive methods, with a correlation index $R^2 = 0.81$ between the measured fluorescence and hardness for apples (Guidetti and Oberti, 1998), The tests on peaches (*cv Vega, Max, Fayette, Sweet lady, Elegant lady*) exhibited a high dependence of the method on the variety of fruit: whereas with the *Vega cultivar* there was a good correlation between the fluorescence value and the chlorophyll content in the epidermis of the fruit (fig.6.a), for the other cultivars the results were, on the contrary, very scattered (fig.6.b).



a) b)

Fig. 6 *Fluorescence intensity vs chlorophyll content using the blue system: a) Vega cultivar; b) Fayette and Elegant lady cultivars*

The tests under a red LED light source were conducted on peaches (*cv Elegant lady, Summer Rich, Max, Royal Gem*) and nectarines (*cv Morisani 90*), with results that - despite exhibiting a consistent trend (fig.7.a) between destructive and non-destructive measurements - are only partially satisfactory for the



a) b)

Fig. 7 *a) Fluorescence intensity vs firmness and b) Hue vs firmness: it is clear the good correlation in the diagram a) and the absence, in diagram b)* classification of the fruits, although they still provide a more reliable indication than colour alone (fig.7.b).

4.2. *Reflectance images*

The reflectance analysis evaluate the reflex ray coming from a sample with a right light. Particularly filters permit to obtain also superficial information like bruises and other injuries to classify the products and to automatize the sorting.

The focus of this research is on the possibilities to reveal the presence of bruises on the product by mechanical operation during or post the harvest, or by the developing of pathogens, like penicillium, during the ripening. The reflectance images are used also to detect the brightness of the strawberries.

The experimental set is composed by a digital camera with or without a monochromator, constituted by a motorised wheel, controlled by a PC, with eighteen filters in the interval between 380 and 1060 nm.

Detection of bruises

The experimentation regarded especially apples (*cv Golden Delicious)*, peers (*cv Decana*) and peaches (*cv Elegant Lady*). The data analysis permit to develop a multispectral method to identify the two more significant wavelengths: to recognised the whole region of the fruit from that pathological one or with a mechanical damage; to combine the information from the two images of the fruit at the two wavelengths identified, and from them to obtain an another "virtual" image in which the injuries are more visible and potentially recognisable from an automatic system. This possibility has to be possible especially for very early injuries.

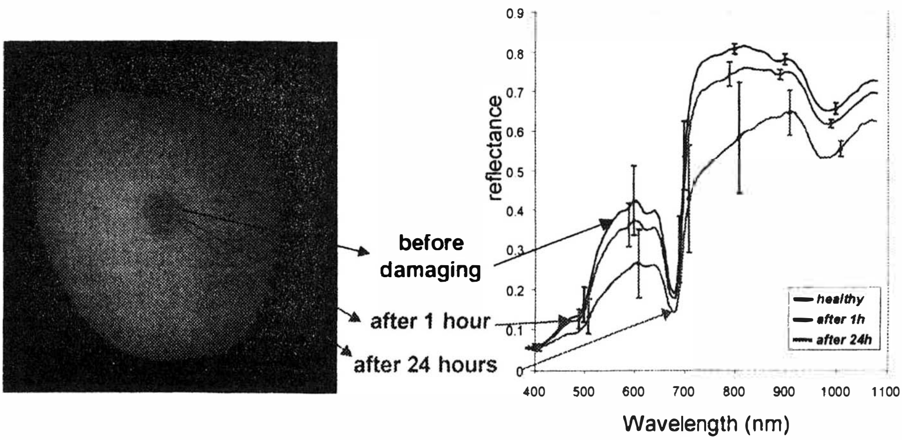


Fig. 8 *Mechanical bruise region in an apple and relative variation of the spectrum*

In the "virtual" images obtained after 24 hours for the mechanical bruises, or after 48 hours for the pathological ones, the interested regions result well defined with a good contrast while, visually, they are identifiable, only with a very carefully observation.

For the mechanical bruises, studied on peers and apples, the more significant spectral couples is formed by 440 nm and 600 nm for peers and 520 and 820 for the apples (fig.8), while the pathological bruises, analysed on the peaches, are well identify in the image obtained directly at 440 nm (fig.9) and the multispectral analysis doesn't supply interesting results.

Strawberries brightness
To develop the previous studies about the brightness is examine closely the mirror reflection and the possibility to use the polarised light. The objective of this study is to arrive to have an index to classify a whole strawberries box.

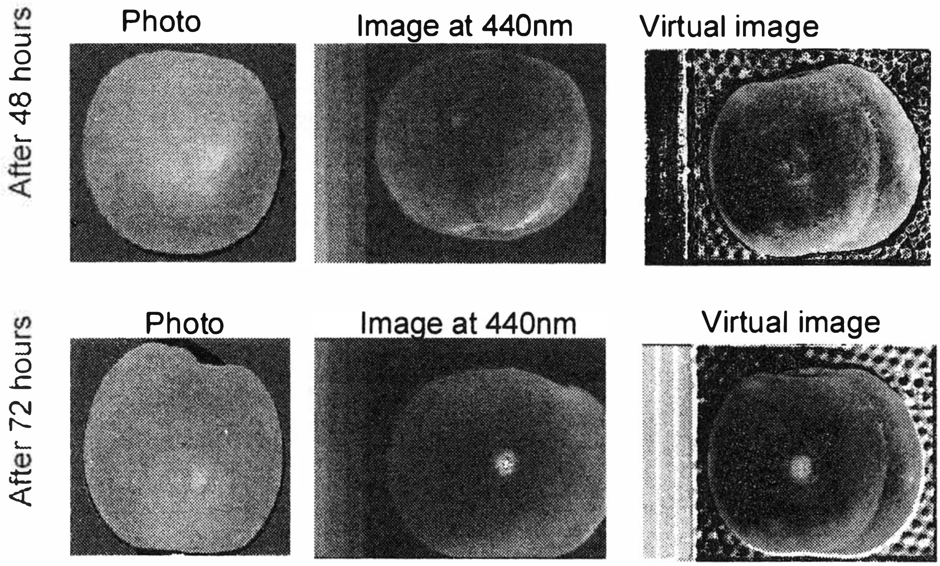


Fig. 9 *Identification of the pathological bruises with the image at 440 nm. The virtual image is obtained with the ratio of the image at 480 nm and 700 nm*

The device used for the research is composed by:
- an halogens light (50 W);
- an acquisition image system formed by a camera and a polarised filter which can rotate on its axis.

With this method it is possible having three image (fig.10): one without the filter, the second one with the polar axis of the filter parallel to the plan of oscillation of the reflected waves, the third one with the polar axis orthogonal to the plan of the oscillation of the reflected waves.

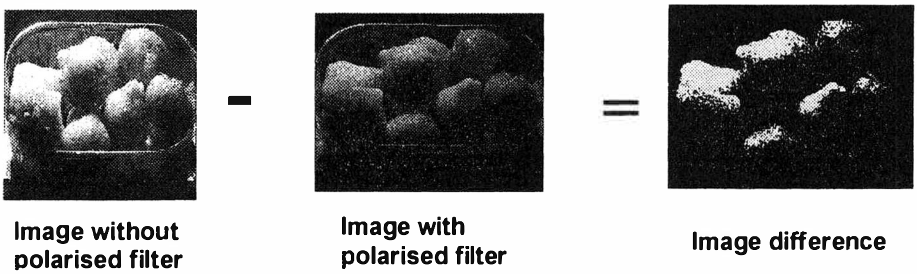


Fig.10 *Three images used to obtain a brightness index (IB) to sorting the strawberries basket for brightness*

The analysis of this three images permits to obtain a brightness index (IB) to separate strawberries which different quality level, given from the ratio between the part of the image which show reflection and the one which doesn't reflect.

5. CONCLUSIONS

Providing the consumer with high quality fruit and vegetables is a complex, multi-disciplinary task that requires agronomical, bio-physiological, technological and modelling contributions. In this regard, one of the most important aspects in which engineering is directly involved concerns the development of methods and instruments for the non-destructive measurement of the physical-chemical properties of the product, and the definition of appropriate relationships with their evolution and specific threshold values.

The researches conducted in the Agricultural Engineering Institute of the University of Milan, show that the physical principles can give right indication about the quality level and ripeness stage of fruit and vegetables. The objective to design low cost and user friendly devices is now within reach. The researches are now ready to involved closely the industrial word and try to realise:

- the increase of the performance of the on line machine with the aim to have a reliable sorting with more products: this means the generalisation of some algorithm to can predict the products characteristics;
- the develop of device very precise for the use of many parameters (sugar content, acidity, nutritional elements, etc.) detecting from the spectral analysis; the use of this device could be dual: it could be a supporter to the agronom-

ic selection and validation and also it could be an help for the consumer that could sort directly the products closely to his own taste;

- an improvement of the device for the standard measurements: e.g. a not destructive refractometer.

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