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Non-Destructive Quality Control in Fruit and Vegetables through Dynamic Response to Acoustic Excitation

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ABSTRACT

The potential use of ultrasonic techniques in the nondestructive quality control of fruits and vegetables was tested and evaluated. In a preliminary study, basic laws and principles of wave propagation within fruit tissues were verified. The power and frequency range of the ultrasonic system were defined and the relationship between properties of some fruits and their response to ultrasonic excitation were tested and analyzed. The study was culminated in with the development of whole-fruit experimental testing methods for avocados and potatoes.

Methods involving narrow-band and broad-band excitation at a frequency range of 50 to 500 kHz were used to identify internal properties in tissue specimens, half-cut fruits and whole fruits, in order to establish relations between the mechanical, acoustical and quality parameters of melons, avocados, potatoes and apples.

Acoustical attenuation of winter-grown melon tissue correlated well with its ripeness and sugar content. Quantitative relations were defined between the size and the frequency of the narrow-band ultrasonic probe and the sound pressure field over half-cut potato and avocado. The same theoretical model could not represent the pressure field in melon.

Although ultrasonic waves could not be transmitted through a whole apple, cylindrical apple tissues were used to investigate its acoustic properties. The ultrasonic wave velocities and the elastic moduli of the three tested apple varieties decreased while the attenuation coefficients of apple tissues increased as the apples became riper.

Nondestructive testing of whole melon and avocado was performed using a narrow-band 50 kHz ultrasonic head comprised of two inclined probes, attached to the fruit peel. Attenuation of the ultrasonic signals correlated well with the color of fresh melons. However, poor correlation was found between ultrasonic peel signals and internal properties of the melon. Repeated tests on whole avocados during ripening indicated that changes in the ultrasonic peel signals may be used for firmness determination of the tested fruits.

Hollow hearts were detected successfully in Atlantic potatoes by using the broad-band direct-transmission ultrasonic method. Fast Fourier Transform techniques were used for frequency analysis of the transmitted signals. Frequencies higher than 150 kHz could not be transmitted through the whole potato; frequencies lower than 50 kHz would probably not give enough resolution for detection of the hollow hearts. Under the test conditions, all hollow-heart potatoes were identified without any failure.

Results of this study show the potential of using ultrasonic testing for nondestructive evaluation of fruit and vegetable quality. Methods are proposed for the detection of hollow heart in potatoes and of firmness in avocado. These methods may be adapted with some modifications to other agricultural commodities. Yet, further study is needed for a refinement of the nondestructive methods and the quantitative relationship between the measurable ultrasonic parameters and the internal quality of the related fruits and vegetables.

1. Introduction

1.1 Background

Quality evaluation of fresh fruits and vegetables can be a complicated operation, whether it is done by destructive or nondestructive methods. Fruits and vegetables are characterized by certain properties that determine whether or not they will be accepted by the consumers. In general, quality may be specified in terms of a number of factors or characteristics, such as appearance (size, shape, color), texture (firmness, tenderness), and flavor (sweetness, acidity, volatile), each of which may be defined and evaluated independently. Quality evaluation of fresh agricultural products is an important aspect of fruit and vegetable production, processing, and handling. High-value fresh agricultural products must be carefully handled, from harvesting through cleaning, sorting, packaging and distribution, in order to maintain the required high quality standard. In each handling stage, quality must be evaluated by individual inspection of appearance of each product, as well as through sampling and destructive testing.

Nondestructive testing and evaluation has been used for many years to evaluate engineering materials, and many of these methods have been utilized to evaluate the quality of agricultural products. The samples that are used to evaluate the quality of a product are not damaged or destroyed during non-destructive measurements. Nondestructive testing and evaluation commonly involves application of a well-characterized source of energy to the test object. The forms of energy that are widely used include light, x-rays, ultraviolet, sonic, and ultrasound. The input energy is applied to a test object and interacts with it, and is modified in some unique manner because of the chemical and/or physical characteristics of the object. In general, the input energy is reflected, transmitted, and absorbed or attenuated as well as scattered internally by the object. The differences between the input energy and the energy response can be analyzed and provide a basis for quality evaluation of the product.

Many methods are available for evaluating the external appearance of a product. These methods are used to define size, shape, color, external mechanical damage and disease symptoms. For internal quality evaluations, such as proper structure and internal damages, etc., it is customary to find some indirect link with the external appearance, such as product color, extent of ripeness or other external conditions of the product. However, quality defects such as hollow hearts in potatoes and watercores in apples exist internally without any external evidence of abnormality. These internal quality factors require non-destructive testing techniques for their detection. Many of the present methods used to measure quality of fruits and vegetables are destructive and slow.

Nondestructive evaluations have several advantages over conventional destructive testing. First, the sample size can be increased, ideally to include every item with no loss of product. Second, subjective assessment is replaced with objective measurements. There is clearly a demand for rapid and non-destructive evaluation techniques for the quality of fresh fruits and vegetables which may enter the fresh-market channel or be used for processing. Such techniques can be of great value in research by monitoring quality changes during storage or in assigning quality grades to fresh fruits

and vegetables. Up to the present time, some possible techniques such as light transmission and reflection, x-ray analysis, and sonic vibration have been investigated most extensively for nondestructive quality evaluation of fresh food materials.

Ultrasonic characterization has been used for many years as a nondestructive testing tool primarily in the metal industry. Ultrasonic nondestructive testing is a way of characterizing materials by transmitted ultrasonic waves (longitudinal, shear, surface, etc.) through the materials or by reflected waves from the materials, and studying the characteristics of the transmitted and/or reflected waves. Correlations of acoustic measurements with test material properties (such as density, porosity, texture, elastic and mechanical properties) establish the basis for nondestructive testing by ultrasound. The acoustic measurements include ultrasonic velocities, frequency-dependent ultrasonic attenuation and/or absorption of reflected and transmitted ultrasonic signals, as well as time and frequency spectra. By using an appropriate theory, ultrasonic measurements can be used to determine the physical properties of the testing material. Therefore, ultrasonic techniques can be useful to investigate the quality of fruits and vegetables since the quality is correlated to the physical properties of the plant tissue of interest.

Ultrasonic nondestructive testing and evaluation of metals in industry and of biological tissues in medicine is an established and very successful technique. In industry, such techniques are used to diagnose internal defects such as voids in weldings and castings; whereas, in medicine they are used to determine normal and abnormal tissues, internal structure of organs in the human body, and the prenatal condition of fetuses. In spite of the wide use and success of these methods in industry and medicine, very little has been done to use this technique for quality evaluation of fresh food products, especially for fruits and vegetables.

Ultrasonic techniques have been used to determine fat thickness in beef cattle, pork, other meat and fish, but have not been used widely for fruits and vegetables. Problems encountered in evaluating these food stuff, using ultrasound, are caused by the nature of ultrasonic wave propagation in complex non-homogeneous media and very high attenuation properties of the biological materials, which are usually porous and contain air in their tissue. Their ultrasonic velocities are low and their attenuation in the frequency range of 1 to 10 MHz is very high. The potential of ultrasonic non-destructive evaluation of plant tissue has been recognized for some time (Sarkar and Wolfe, 1983). However, very high attenuation of ultrasound by the plant tissue has tended to limit studies to only thin slice samples (< 10 mm) and this reduces the accuracy of ultrasonic measurements. It has been suggested that the scattering of ultrasonic energy, including resonant scattering, from the intercellular air space existing in most plant tissue, is largely responsible for the high attenuation. Because of high attenuation, it is difficult to transmit ultrasonic waves through whole fruits and vegetables. The measurements reported so far have been in the frequency range of 50 kHz to 1 MHz. The difficulties caused by high attenuation may be overcome by using lower frequency range and by increasing the input power.

Therefore, it is necessary to determine the suitable frequency and required power of ultrasonic waves for various agricultural products, to build the appropriate equipment, and to test its potential

use with tissue samples and whole fruits and vegetables. Specific optimum frequency for a given test material and the test objectives should be determined. The optimal ultrasonic frequency is the highest acceptable frequency for a given material that results in minimum attenuation and maximum resolution.

Ultrasonic measurement has potential advantages over other techniques including freedom from radiation hazards, which may appear in some of the existing non-destructive methods, such as x-rays, and ease of automating the food quality detecting system. Also, sample preparation required for utilizing ultrasonic methods with whole fruits and vegetables might be simpler than other methods requiring a sample from the product. In general, ultrasonic waves are capable of propagating in any medium with the exception of a vacuum, and ultrasonic method could be applied to virtually any size or shape of the test material. Investigation of reflected or transmitted ultrasonic waves from a material of propagation can provide important information about the properties of the material. Therefore, it is possible to evaluate a wide variety of materials and processes by ultrasound. And yet, the equipment used in medicine and industry is apparently not suitable for examination of fruits and vegetables. Other critical factors regarding the quality evaluation operation are penetration depth and resolution.

Resolution, which is dependent to a large extent on the ultrasonic wave length (and consequently the frequency), improves at higher frequencies. However, the attenuation of ultrasonic signals increases as a function of frequency with a concomitant decrease in penetration depth. Therefore, the proper frequency ranges and signal analysis methods for evaluation of the quality of fresh agricultural products need to be identified. Many possibilities of ultrasonic non-destructive evaluation of fruit quality, fruit structure and its internal defects have been acknowledged in the literature survey. The rapid developments of sensors, micro-computers, and signal analysis methods have opened new possibilities for application of this simple and non-hazardous testing method.

1.2 Objectives

The general objective of this research is to investigate and use ultrasonic measurement techniques to characterize various fruit and vegetable properties that are related to their quality. The specific objectives are:

1. Verification of basic laws and principles of wave propagation within fruit and vegetable tissues;
2. Screening and classification of potential fruits and vegetables which are suitable for acoustic testing;
3. Systematic study of relationship between quality of some selected products and its acoustic responses;
4. Development of a laboratory prototype of a whole fruit acoustic testing system, dedicated for non-destructive quality control of fresh agricultural products.

2. Literature Review

Ultrasonic waves are simply high-frequency sound waves above the upper limit of human hearing. Sound is usually caused by a vibrating body. Human beings can only hear sound when these vibrations are between about 16 and 16,000 Hz. The sound source produces a sound wave in the medium of transmission. The vibrations of the sound source cause molecules of the surrounding medium to vibrate back and forth about an average position and each particle transmits motion to an adjacent particle. Sound and ultrasound waves, which cause mechanical vibrations of particles in the medium, can be transmitted in solids, liquids, and gases. In fact, liquids and solids are better conductors of sound than air. Sound travels through air at about 330 m/s, but moves more than 4 times faster in water (about 1400 m/s) and about 18 times faster in steel (about 6000 m/s) (Brown and Gordon, 1967). In general, the more stiff (resists to change of shape or volume) and elastic the medium, the greater the velocity of sound in it, and the less power required to transmit sound energy through a given distance.

2.1 Acoustic Impulse and Resonance Techniques

Acoustics have been successfully used to measure the texture or firmness of fruits and vegetables. The response of materials to sonic energy is influenced by such factors as elasticity, size, shape, mass, density and texture of the material. Responses are usually measured in terms of vibration amplitude, frequency and damping characteristics. The larger the size and the softer the texture is, the lower will be the resonant frequency. Rapid acoustic decay is a characteristic of high internal friction which is responsible for the absorption of vibration energy in a material. A number of studies have been conducted to correlate sonic response to some other indices of fruit and vegetable quality, such as pressure test and sensory panel ratings. The study showed a significant correlation between the non-destructive sonic measurements and fruit texture (Finney, 1978).

Finney *et al.* (1967) were successful in detecting changes in firmness of ripening bananas, through correlation between Young's modulus and resonance frequency. They used cylindrical sections of pulp removed from bananas and vibrated them longitudinally. The resonance frequency was determined and correlated with modulus of elasticity. Softening of the banana during ripening was associated with a decrease in Young's modulus of elasticity. Finney and Norris (1968) found a sound correlation between moduli of elasticity of whole fruits and fruit samples and their natural frequency. The technology of sound analysis used in their study was based on a relationship between natural frequency and maturity of the products.

Texture is one of the important quality factors of fruits and vegetables. Sonic and vibration response method is one technique for predicting the texture quality of agricultural products nondestructively. With sonic technique, Abbott *et al.* (1968/a) studied two ways to measure the inner texture of fruits and vegetables. In one method, cylindrical sections cut from an apple were vibrated at their natural frequencies, and internal friction and Young's modulus were calculated from the data.

In the other method, sonic energy was applied to a whole apple, resulting in a series of resonances. They found that the second resonant frequency in apples was strongly influenced by fruit size and firmness: the smaller and firmer the fruit, the higher the resonant frequency. To compensate for variations due to differences in fruit size or mass, they found that a "stiffness coefficient" f^2m , where f is the resonant frequency of the apple and m is the mass of the apple, could be used as an index of apple firmness. The results of the sonic vibration studies indicated that f^2m of whole fruits was highly correlated with the elastic modulus of the fruits, and the natural resonant frequency of the fruits decreased as they aged or ripened after harvesting with the firm fruits transmitted higher frequency energy than soft fruits. Therefore, measurement of stiffness coefficient could be used as a non-destructive method for measuring and studying aging as well as firmness of apples at a given time.

Finney and Abbott (1978) and Morrow and Mohsenin (1968) reported that the velocity of propagation of acoustic waves through solid foods is a measure of food firmness. Garrett and Furry (1972) used the propagation velocities of various sonic waves through the intact and sectioned apples for measurement of mechanical properties such as Young's modulus, tissue density and Poisson's ratio.

Clark (1975) also used the propagation of acoustic waves through a whole watermelon to predict its ripeness. He conducted a research in which a pendulum struck a watermelon, producing characteristic sound waves which were detected by a wave sensor. The time decay of reflected and transmitted sound waves through the whole melon was studied. It was found that there was a high correlation between decay time of reflected and transmitted sound and meat color of the watermelon. The decay time increased as the melon meat matured. However, the regression analysis relating the decay time to the Magness-Taylor test had very low regression coefficient. Similarly, Armstrong *et al.* (1989) reported poor correlation between the resonant frequency of apple and Magness-Taylor firmness. In fact, Magness-Taylor firmness is a measure of the crushing and shearing strength of the tissue rather than its elastic properties and this may account for the poor correlations. Armstrong *et al.* (1989) used acoustic emission of an apple, as a result of impulsive excitation, to find resonant frequencies of the apple. The observed resonant frequencies were used in an elastic sphere model developed in their study to predict firmness of the apple. The modulus of elasticity of the apple was predicted from the acoustic resonant frequency vibrations caused by an impulse striking the apple. These predictions were compared with measured values of Magness-Taylor firmness and modulus of elasticity of the apple. Good correlation existed between modulus of elasticity measurements that included the apple core in test specimen and the predicted elasticity. Poor correlation existed between the predicted elasticity and Magness-Taylor firmness.

2.2 Ultrasonic Techniques

There are three basic reasons why ultrasonic energy is used in most applications rather than sound waves. First, many applications require high acoustic power. Since ultrasonic frequencies

cannot be heard, powerful ultrasonic waves may be used without causing intolerable noise. Second, high ultrasonic frequencies with corresponding small wavelengths are useful for applications of nondestructive testing (NDT). The higher the frequency and the shorter the wavelength, the smaller the flaw which can be detected. Third, ultrasonic frequencies are useful for generating directional waves in many applications. Smaller transducers can be used to send out a "search-light" beam.

2.2.1 Ultrasonic Techniques in Food Products

The use of ultrasonics to evaluate various properties of some foods goes back about 30 years. Ultrasound was used to determine albumen quality of eggs shell (Mayer *et al.*, 1957), fatness in swine (Hazel *et al.*, 1959), fat thickness in cattle (Stouffer *et al.*, 1961; Johnson *et al.*, 1964), in pork (Lynch 1967), and in fish (Freese and Makow, 1968). The earliest investigation of the use of ultrasonics to grade whole eggs was carried out by Mayer and Hiedemann (1959). They attempted to determine whether or not it was feasible to develop and evaluate ultrasonic methods for measuring albumen quality of shell eggs and to relate these qualities to the grade of the eggs. They concluded that ultrasonic measurements would not be useful for reliable grading of eggs. However, their research suffered from the use of very crude experimental techniques and their conclusion could not be accepted without further experimentation.

Povey and Wilkinson (1980) reported their work on an application of ultrasonic pulse-echo techniques to albumen quality testing of eggs. They studied the components of the egg (yolk, thick white, bad thin white) in an attempt to find a distinguishing feature which would permit the design of ultrasonic quality control equipment for whole eggs. Their measurements were carried out at ambient temperature (14 to 17°C) and at 1.25 MHz. The most obvious feature of the results was the higher attenuation of the thick white compared with that of thin white. Their results indicated that the attenuation may be used as an indicator of egg quality through the variation in acoustic properties between thick and thin white. As egg ages, the ratio of thick white to thin white decreases and the attenuation of the ultrasound transmitted through the egg should decrease as well, due to the lower attenuation of the thin white in comparison with the thick white. They concluded that the attenuation difference between thick and thin white may be an appropriate measure for automatic, non-destructive testing of the eggs.

Javanaud *et al.* (1984) made more accurate measurements of the velocity and attenuation of ultrasound in both egg white and egg yolks. Their results, however, did not support Povey and Wilkinson's tentative suggestion of a fall in the ultrasonic velocity in eggs with age. The measurements were made at frequency range 2 MHz to 124 MHz over the approximate temperature range 20 to 25°C. They found that the values of ultrasonic velocity and attenuation lied within a much narrower range than those quoted by Mayer and Hiedemann (1959). The egg white and egg yolk had very different ultrasonic characteristics. The temperature coefficient of the sound velocity in the former was very close to that of water, while that of the latter could not be detected. The negative temperature coefficient of absorption in the yolk showed up quite clearly, although that of the white was quite small. The frequency dependency up to 124 MHz of absorption was close to linear in the

white (exponent 1.2) and slightly greater in the yolk (exponent 1.5). The more recent work by Choi *et al.* (1986) has found no significant difference between thick and thin part in the frequency range of 0.2 to 10 MHz over the temperature range 10 to 50°C. No aging effect of egg white measurement in absorption was observed when the experiment was repeated at 20°C after 8 days to find the aging changes. Their results showed a very good quantitative agreement with the results of Jaranaud *et al.* (1984).

Miles and Cutting (1974) studied changes in the velocity of ultrasound in lean beef during freezing in order to estimate the ice content of the frozen meat by a direct measurement of the pulse transmission time. The velocity of ultrasound is greater in ice than it is in water. The results showed that the velocity through the unfrozen meat changed only slightly with temperature over the temperature range 0 to 10°C. At the beginning of freezing, the velocity of sound increased rapidly with reducing temperature. At a temperature of -5°C, when food materials such as meat are generally regarded as substantially frozen, the ultrasonic velocity increased by 70% of its unfrozen value. As temperature was further reduced, the rate of change in velocity with temperature declined progressively. At -20°C, the velocity was roughly double that at 0°C. They also demonstrated that the acoustic velocity could be used to estimate the mean specific enthalpy of partially frozen meat, which is a physical parameter that is important in the design of refrigeration systems.

Miles and Fursey (1976) studied the fat content of beef carcass meat using ultrasonic waves over the temperature range -20°C to +40°C. They found that measurements at 37°C appeared to have the best predictive value, and at that temperature, there was a linear relationship between the fat content and the reciprocal of the velocity of ultrasound measured at 2.5 MHz. Liquid paraffin was used as an acoustic couplant. An electronic system automatically measured the time of flight of an ultrasonic pulse from one side of the carcass to the other, recorded the distance separating the transducer faces and computed the ultrasonic wave velocity. The measurement of the time taken for a pulse to travel through meat consisting of multiple, parallel layers of muscle and fatty tissue of arbitrary fatness could be used to estimate the overall mean volume fraction of fat. They indicated that this property could be useful in assessing the composition of the soft tissue of living animals at selected sites.

Crispness is an important textural quality characteristic of some foods. Povey and Harden (1981) investigated the possibility of the ultrasonic pulse-echo technique as an objective method of measuring the crispness of biscuits. They overcame the problem of coupling of the ultrasound by using soft-tipped probes. They concluded that an encouraging linear relationship existed between the crispness and the ultrasonic velocity of 1.5 MHz longitudinal wave. They were more than 80% certain that this relationship was not an accidental one. A similar but less convincing relationship was found between crispness and ultrasonic attenuation. Young's moduli calculated from the velocity measurements and measurements of biscuit density were also compared with the crispness. However, the ultrasonic velocity showed a better correlation with crispness than does the ultrasonically derived Young's modulus, or the Instron derived modulus. They concluded that the

ultrasonic technique could be promising as a method for the electromechanical measurement of the crispness of biscuits.

The development of the applications using ultrasonic techniques with food materials has been done mainly by velocity measurements, although attenuation, reflection, and frequency spectrum analysis have also been used. The method which has had the greatest success is that of measuring the velocity of an ultrasonic wave by timing its passage through a sample of known thickness. Ultrasonic velocity has been used as a valuable non-destructive technique because of its relative ease of measurement, ease of interpretation of the consequent data, and an accuracy greater than attenuation measurements.

2.2.2 Ultrasonic Techniques in Fruits and Vegetables

Ultrasonic measurements on fruits and vegetables differ from those such as meat because these materials are usually porous and air-containing. The ultrasonic wave velocities of fruits and vegetables are low and their attenuation in the frequency range 1 to 10 MHz is very high. Thus ultrasonic measurements so far have been limited to the frequency range of 50 kHz to 1.0 MHz.

The frequency of the ultrasonic wave is a very important factor in fruit tissue penetration. Sarkar and Wolfe (1983) conducted an investigation to assess the potential of ultrasonic techniques for quality detection of fresh and processed foods using conventional ultrasonic diagnostic equipment. They investigated attenuation properties of potato, cantaloupe and apple tissue, stability of reconstituted orange juice, and skin characteristics of orange and tomato. All the measurements were conducted using an immersion tank with water as the couplant. They found very high attenuation coefficients of the ultrasonic wave at a frequency of 0.5 to 1 MHz in tissues of potato and cantaloupe due to the porous nature of these tissues. The measurements could not be made with apple tissues thicker than 3 mm at 500 kHz due to the high attenuation of the tissue. Furthermore, it was observed that the attenuation coefficient decreased with immersion time and degassing for the potato samples. The primary reason for this decrease was because the water used as the couplant entered the intercellular void spaces by osmosis, and degassing the tissue under vacuum replaced more of the intercellular void space with water. They concluded that achieving penetration for fresh fruits and vegetables to detect internal defects was unlikely with the available diagnostic equipment unless suitable equipment became available. The authors pointed out that at lower frequencies (100 to 500 kHz), acoustic radiation from a transducer of higher energy output might be helpful for fresh fruits and vegetables. They also proposed a method for ultrasonic measurement of the smoothness of citrus fruit peel and detected skin cracks in tomatoes and defects in husked sweet corn by analyzing the reflected signals. However, the immersion technique for fruits and vegetables used by Sarkar and Wolfe was unsatisfactory since the attenuation coefficient decreased with time as liquid entered the intercellular voids of the tissues. Voisey and Hamilton (1976) studied the relationship between egg shell thickness and ultrasonic measurements using water as the transmission medium, and they had a similar problem which could affect the measurements used in the egg shell thickness determination.

Bruises in apples are quality defects and are of primary concern when defining the quality of apples. Bruising of fruits often increases with the use of mechanical harvesters and bruised apple tissue is very difficult to detect immediately after being damaged. Spectral analysis of reflected ultrasonic acoustic signals for damage detecting in apples was carried out by Upchurch *et al.* (1985). They reported that undamaged samples of apple tissue contained more air spaces than samples from damaged areas. Therefore, undamaged apple tissue had a very high mismatch of acoustic impedance causing most of the wave energy to be reflected at the surface. The large acoustic mismatch of the undamaged tissue may be caused by the 23% gas composition of the tissue (Mohsenin, 1984). On the other hand, when the tissue is damaged, the cell walls rupture releasing their contents into the air-filled interstitial spaces, therefore exhibiting a lower acoustic impedance. The reflected signal for the damaged tissue showed a very low amplitude reflection at the surface while the reflection from the back side of the damaged area contained more energy. However, the acoustic impedance mismatch at the damaged-undamaged interface was large causing a second reflection from the interface. For tests with peeled apples, the authors pointed out that the power spectrum composition of undamaged and damaged tissues was substantially different. The spectral composition of the two signals showed a difference in the signal power distribution at different frequencies. However, the results of earlier tests with unpeeled fruits indicated the lack of penetration of wave energy through the peel and failed to indicate any differences between damaged and undamaged sites. This lack of penetration may be due to a wax coating which is present on the skin of the fruit.

Upchurch *et al.* (1987) later developed computer and physical models demonstrating an ultrasonic technique for distinguishing between damaged and undamaged apple tissue. The assumption they used was that the presence of frequency nulls in the power spectrum of the reflected signal provided a feature for distinguishing between the two simulated tissue types. The reflected signal for undamaged condition contained a single reflection from the outer layer. For the simulated damaged condition, the received signal contained a reflection from the outer layer and a second time delayed reflection. Therefore the damaged conditions were indicated by the interference patterns in the power spectrum. One of the important features of this approach was the possibility of distinguishing between tissue types independent of the angle of incidence or elasticity differences within the tissue type. However, tests with intact fruit without the cuticle did not exhibit additional frequency nulls for damaged sites as described in the models because of the high attenuation property of the tissue, although a difference existed in the power spectrums between damaged and undamaged tissues. For the results from intact fruit with the cuticle, the difference between the damaged and undamaged tissue was undetectable. They concluded that the skin of apples was the major reason for the high acoustic impedance, and apple tissue was a strong attenuator of ultrasonic signals. The incident wave did not penetrate to the boundary between the bruised and unbruised tissue.

Povey (1989) investigated a very wide range of fruits and vegetables, using a pulse transmission technique at 500 kHz. In their investigation, in no case was it possible to transmit the ultrasonic energy through a whole fruit or vegetable at this frequency using his instrumentation. The measurements reported were obtained by first pressing the transducers together, marking the time

position of the transmitted pulse leading edge and then inserting a slice of material between the transducers. The time-of-flight for the sample was then determined. The results of his research illustrated a common feature of measurements on food materials - the variations of the measurements for fruits and vegetables are fairly large. Among the fruits and vegetables investigated by Povey (1989), in some products such as yellow and green peppers, melon of various varieties, aubergine, mushrooms, banana, cucumber and English onions, no sound was transmitted through the 5 mm slice at 500 kHz. The author suggested that this was the result of air scattering in the tissues of the fruits and vegetables. On the other hand, the ultrasound at 60 kHz was transmitted through 5 mm slices in Kiwi fruit, swede, apple, pears and peaches. However, Povey observed that it was not possible to make velocity measurements at 60 kHz because of errors in determining the position of the leading edge of the output signal.

Detecting internal defects of potato tubers by using ultrasonic waves is a relatively new developing technique. Watts and Russell (1985) have attempted some initial study on use of ultrasonics for detection of potato tubers with hollow heart. The major problem they encountered with the ultrasonic system resulted from the high attenuation characteristics of the tissue making up the potato tuber, especially at high frequencies. At low frequencies, resolution decreased and a large transducer was required. Also due to the high attenuation coefficient a pulse echo technique requiring only one transducer could not be used. Instead, a through-transmission technique must be used requiring a transducer on both sides of the tuber. The difficulties encountered also dealt with the design of an appropriate transducer. The other problem they encountered included the requirement for an acoustic couplant, such as water or other wetting agent at the point of contact between the transducer and the potato. However, the authors expressed confidence that the method was feasible and could be made to work. They stated that potential benefits of an ultrasonic detection system are reduced health risk as well as reduced costs.

2.2.3 Other Applications of Ultrasonic Testing in Agriculture

Bucur and Muller (1987) investigated a novel application of the ultrasonic velocity method to separate germinated and non-viable acorns and in this way to predict their germinability based on morphological and physical criteria (density, ultrasonic velocity, etc.). They suggested that the ultrasonic velocity is undoubtedly of considerable value in investigations of the internal structure of acorns, in the assessment of their properties, and in the design of systems for their quality evaluation. The ultrasonic velocity was determined using the classical through-transmission method for solids. They found that the germinability was related to density and ultrasonic velocity - a high density and a high ultrasonic velocity characterize a viable acorn. They suggested that such a technique, completed with other propagation parameters of ultrasonic waves, could be applied to other forest seeds, and might provide a useful characterization technique for the evaluation of germinability, detection of defective or poorly developed acorns.

Micra *et al.* (1989) used acoustic transmission methods and frequency-domain analysis to characterize the quality of soybean. The results indicated that it was feasible to acquire and analyze

the acoustic transmission data of soybeans and that differences between kernels of good and poor quality could be observed. But the spectrum of acoustic transmission could not be described in any mathematical manner, so there was no way of correlating the transmission spectra with the size or mass of soybeans.

2.3 Summary of Literature Survey

In the light of the literature survey, many possibilities of ultrasonic nondestructive detection of fruit quality, fruit structure and its internal defects have been acknowledged. However, the equipment used in medicine and industry is apparently not suitable for examination of fruits and vegetables. In order to apply this technology to agricultural products, it is necessary to determine the suitable frequency and required power of ultrasonic wave propagation for various products before the appropriate equipment can be built.

The major problem of ultrasonic testing resulted from the high attenuation characteristics of the fruit tissue, especially at high frequencies. At low frequencies, resolution decreases and a large transducer is required. In this case, energy focusing devices have to be used. Due to the high attenuation coefficient a through-transmission technique must be used. Another problem encountered is the requirement for a proper acoustic couplant, such as water or other wetting agent, or special designed dry-coupling transducers; good and accurate coupling is necessary for accurate attenuation measurements. Accurate measurements of the position of the leading edge of the output signal should be made for determination of wave velocity, especially at low frequencies. When all these technical difficulties are overcome, ultrasonic screening of potential fruits and vegetables have to be made and a proper signal analysis be selected for quality evaluation of selected products.

3. Verification of Basic Laws and Principles

Sound waves are produced as a result of the mechanical vibration of the molecules, atoms of a gas, liquid, or a solid material about the equilibrium positions of these particles. Vibration of particles in a material is an essential characteristic of acoustic propagation and for this reason, it is impossible for sound to pass through a vacuum. When a sound wave strikes material, its particles are set into motion. If a particle is displaced from its equilibrium position by applied stress, such as by the pressure of a sound wave, internal forces in the particles tend to restore the system to its original equilibrium position. Since a material composed of infinite particles mechanically coupled to each other, when one particle is displaced from its equilibrium position, it exerts pressure upon the next one. Therefore, displacement at one point induces displacement at the neighboring points. The transmission of a wave through a medium is the result of the combined effects of elastic force between particles and inertia of the particles.

Sound waves undoubtedly are capable of providing useful information about the media through which they travel. Ultrasound is actually an extension of audible sound and differs from the sound waves just in magnitude, not in principle. Ultrasonics is the name given to the study and application

of sound waves having frequencies higher than those to which the human ear can respond. Ultrasound wave is elastic in nature and can be characterized by wave motion. Transmission of these waves is essentially dependent on particle vibration, each particle of the medium being displaced subsequently as the wave travels through the medium. Any material possessing elasticity can support the propagation of an acoustic wave. The elasticity can provide a restoring force that tends to return each element of the material to its starting point. Therefore, ultrasonic waves, when propagate in a material, actually cause particle displacements in it. The amount of displacement or elasticity is a function of intrinsic behavior of a material. Thus for all practical purposes, once propagated in a material, ultrasound generates the phenomena of reflection, refraction, transmission, diffraction, interference, scattering, and dispersion as it interacts with the material. Investigation of these phenomena in light of test material characteristics is the key to nondestructive testing and evaluation. The significance and quality of information revealed by ultrasound are related directly to the performance of incident and receiving components of the ultrasonic characterizing system.

The various applications of ultrasonics may be classified under two headings: (1) Low intensity ultrasonics, (2) High intensity ultrasonics. With low intensity applications, the waves are used to investigate the physical properties of the material through which they pass and the material does not suffer any permanent changes. With high intensity applications, actual work is done by the waves on the material, e.g., the production of cavitation, heating, drilling, etc., and irreversible changes in the properties of the material can often take place. Therefore, for nondestructive applications, low intensity of ultrasonics are widely used.

3.1 Types of Ultrasonic Waves

Depending on the mode of particle vibration relative to the direction of wave propagation, ultrasonic waves can be classified into three categories: longitudinal, shear and surface waves. Each of these may be utilize in Nondestructive Testing (NDT) as explained below.

3.1.1 Longitudinal waves

When the direction of particle displacement is the same as the direction of wave propagation, the wave produced is called a longitudinal wave. These waves are characterized by alternate rarefaction and compression of the particles along the direction the wave is propagated. The velocity of longitudinal wave in water is 1400 m/s, and for air is 330 m/s. This wave type is commonly used in NDT and the only type that can be transmitted in liquids and gases. Unless stated otherwise in this study, only longitudinal waves will be considered. This is because longitudinal waves are the easiest to generate and detect and thus by far the most widely used.

3.1.2 Shear waves

When the direction of particle displacement is perpendicular to the direction of wave propagation, the wave produced is called a shear wave. For the transmission of the shear waves, shear forces must exist between the molecules or particles so that as one particle moves back-and-

forth, it pulls its neighbor with it. In most low-viscosity liquids and gases, the forces of attraction are so small that shear waves cannot be transmitted through them. Shear waves are used to detect weld defects as well as defects whose orientation is angular relative to the test surface.

3.1.3 Surface waves

Surface waves are transmitted on the surface of the solid while hardly affecting the material beneath the surface, very much like waves on the surface of a lake. Surface waves are characterized by complex motion of longitudinal and shear waves, i.e. the particle vibration is both longitudinal and transverse. In NDT, surface waves are used for the detection of surface defects in parts having limited or difficult access.

All three types of waves are used in ultrasonic NDT. Investigation of materials with longitudinal waves can be used to reveal sub-surface and bulk-body defects, thickness measurements; and by angulating these waves, transversely oriented defects can also be studied. Longitudinal and shear waves can be applied to determine elastic constants, densities and porosities of materials. Surface waves can be used for the detection of surface-breaking defects. Investigation of these waves, when they are applied to a material, can reveal important properties of the material.

3.2 Reflection and Transmission

When an ultrasonic wave passing through one medium reaches the boundary of that medium and strikes a dissimilar medium, part of the wave energy is reflected back through the original medium and the remainder is transmitted into the second medium. The amount of reflection is determined by the nature of the two media. The relative intensities of the transmitted and reflected waves with respect to the incident waves are expressed by the transmission and reflection coefficients, which are dependent upon the difference in the acoustic impedances of the two media at the boundary. The acoustic impedance, which is also known as acoustic density, for a particular medium is:

$$z = \rho V \quad (3.2.1)$$

where

z = the acoustic impedance for the medium,

ρ = the density of the medium,

V = the velocity of sound in the medium.

Acoustic impedance is associated with the dissipation of ultrasonic energy. For the normal incidence of ultrasonic waves, there is no mode conversion of wave propagation. Using the acoustic impedances for the two media at a boundary, the reflection coefficient R for a wave at normal incidence is given by the expression:

$$R = \left[\frac{z_2 - z_1}{z_2 + z_1} \right]^2 \quad (3.2.2)$$

The transmission coefficient T at the boundary for a wave at normal incidence can be calculated from:

$$T = \frac{4z_1 z_2}{(z_1 + z_2)^2} \quad (3.2.3)$$

where

z_1 = acoustic impedance for the first medium,
 z_2 = acoustic impedance for the second medium.

For a given boundary, the transmission coefficient and reflection coefficient are added together to unity, i.e., $T + R = 1$. The closer the acoustic impedance values of two media, the less reflection occurs and more transfer of energy from one medium to the other. This is an important consideration when it is desired to transfer maximum acoustic power from a transducer to a medium with a minimum of reflection.

The acoustic impedance for biological tissue is very difficult to determine theoretically, because the value of the elastic constants are needed. In biological tissue, the elastic constants can vary with turgor pressure, geometry and size (Mohsenin, 1984).

3.3 Attenuation of Ultrasound Waves

The amplitude of the ultrasonic wave can be attenuated as it travels through the medium due to scattering or absorption of the wave energy. Losses of ultrasonic energy can be expressed in terms of attenuation coefficient α (neper per cm). The attenuation shows the classical exponential dependence of path length:

$$\xi(x) = \xi_0 e^{-\alpha x} \quad (3.2.4)$$

where ξ_0 is the maximum strain amplitude at a reference point, $\xi(x)$ is the strain amplitude at a point x centimeters along the sound path from the reference point and α is the attenuation coefficient in nappers/cm. Either longitudinal waves ($\xi \parallel x$) or shear wave ($\xi \perp x$) may be used. The strain field is converted into a voltage in the transducer. For plane progressive ultrasound waves, attenuation coefficient α is defined by the following equations:

$$A = A_0 e^{-\alpha x} \quad (3.2.5)$$

where A_0 is the amplitude at the reference position in the sound wave and A is the amplitude after travelling a distance x , α is the attenuation coefficient of the medium for a given frequency. The attenuation coefficient α is a measure of the rate at which an ultrasonic wave decreases in intensity by other than geometric means as a function of distance as it propagates through a median. Attenuation measurements are generally useful only when made over a range of frequencies because the frequency dependency of attenuation is closely tied to material properties.

Since acoustic intensity is proportional to the square of acoustic displacement, Eq. (3.2.5) can also be expressed in terms of intensity:

$$I = I_0 e^{-\alpha x} \quad (3.2.6)$$

where x is the distance traveled, and α is the attenuation coefficient, I is the intensity of the wave after it has travelled through a material of thickness x , I_0 is the intensity of the sound wave at the reference position. It is common practice to relate the intensity to some reference value using the decibel scale, as follows:

$$\text{Number of decibels} = -10 \log (I/ I_0) = -20 \log (A/ A_0) \quad (3.2.7)$$

A comparison of Eq. (3.2.7) with Eqs. (3.2.5) and (3.2.6) shows that attenuation can also be expressed in decibels per cm. It can be seen that 1 neper is equivalent to 8.686 dB.

Attenuation of ultrasound in a material has two important sources - scattering and absorption. Therefore, attenuation coefficient can be broken down into two components

$$\alpha = \alpha_a + \alpha_s \quad (3.2.8)$$

where α_a is the absorption coefficient, and α_s the scatter coefficient. However, the mechanism is different for both of them. Scattering of the ultrasonic energy is caused by non-homogeneities within the medium such as internal defects, porosity, boundaries and other physical heterogeneities. The interface of each discontinuity within a medium serves as a reflecting surface, the size of which (in relation to the wavelength) determines its effect as a scatter. Most scattered energy no longer moves only in the original direction of propagation and thus the total amount of energy transmitted is reduced. When scattering occurs, the amplitude of the scattered wave is proportional to f^n , where f is the frequency of the ultrasound. Thus greater scattering occurs at higher frequencies. The other significant source of attenuation is absorption, which is the result of the wave energy being converted to an alternate form of energy such as heat. Absorption is mainly caused by (1) internal friction

(viscosity); (2) elastic hysteresis; (3) heat conduction; (4) other factors, such as relaxation phenomena, molecular structure, etc. In solids, (1) and (2) are dominant, while (3) and (4) are negligible. The attenuation coefficient is always larger than the absorption coefficient because absorption is only one of the means by which the ultrasound wave is attenuated (Stewart, et al., 1982).

The attenuation coefficient yields information about absorption and scattering processes occurring in the specimen and is an important factor for material characterization. First, it determines the amount of acoustic energy which can reach structures of interest at various depths in a medium. Second, it is important because part of the attenuation is due to the absorption process in which the propagating energy is permanently converted (for example, into heat energy which may cause a temperature rise in tissue). Third, attenuation by scattering can result in ultrasonic energy reaching structures not intended to be insonated or in production of standing waves, creating peaks and nodes in the spatial distribution of the ultrasonic energy (Stewart, et al., 1982).

Since the attenuation coefficient α changes with frequencies, mere comparisons of the amplitudes of successive reflections from a material for the estimation of attenuation by $\alpha = -20 \log (A/A_0)$ should not be regarded as a measurement of accurate and precise attenuation of the wave, where A_2 is the amplitude or voltage of a multiple reflection and A_1 is the amplitude or voltage of another reflection immediately preceding A_2 . In order for ultrasonic attenuation to assume a meaningful relationship with properties of a material, it must be defined as a function of frequency. Ultrasonic attenuation in a medium generally increases with increasing frequency in a manner that can be expressed approximately (over a limited frequency range) in the form

$$\alpha = \alpha_0 f^n \quad (3.2.9)$$

where α is the amplitude attenuation coefficient of the medium at a frequency f , α_0 and n are constants for the medium.

3.4 Ultrasonic Parameters

The ultrasonic propagation parameters that can be measured from biological materials such as fruit and vegetable tissues are velocities and frequency-dependent attenuation. However, there are several material properties of interest: texture, density, elastic moduli, and other engineering properties. Since this subject is new in food engineering field, not much is known about the relationship between ultrasonic parameters and properties of foods, such as fruits and vegetables, and experimental research into ultrasound-food interaction phenomenon is needed.

3.4.1 Velocities of ultrasound

The velocity of sound is a constant quantity for a material in a given state and depends only on its physical properties. There are three main types of ultrasound characterized by the modes of

particle vibration relative to the direction of the wave propagation. There are longitudinal, shear, and surface waves. All of these velocities can be measured by the various methods. They are directly related to the following various elastic constants:

$$V_l = \left[\frac{E(1 - \mu)}{\rho(1 + \mu)(1 - 2\mu)} \right]^{\frac{1}{2}} = \left[\frac{K + 4G/3}{\rho} \right]^{\frac{1}{2}} \quad (3.2.10)$$

$$V_t = \left[\frac{E}{2\rho(1 + \mu)} \right]^{\frac{1}{2}} = \left[\frac{G}{\rho} \right]^{\frac{1}{2}} \quad (3.2.11)$$

where

V_l = longitudinal wave velocity

V_t = transverse or shear wave velocity

E = Young's modulus of elasticity in the direction of measurement

G = shear modulus of elasticity in the direction of measurement

ρ = density of the material in the direction of measurement

μ = Poisson's ratio

K = bulk modulus of elasticity, $K=E/ 3(1-2\mu)$.

The above equations are valid only when the diameter of the solid is larger than the length of the propagated wave. Surface waves are more complicated than longitudinal and shear waves. The velocity of surface wave is related to longitudinal and shear wave velocities through the relationship

$$\left(\frac{V_r}{V_t} \right)^6 - 8 \left(\frac{V_r}{V_t} \right)^4 + 8 \left(\frac{V_r}{V_t} \right)^2 \left[3 - 2 \left(\frac{V_t}{V_l} \right)^2 \right] - 16 \left[1 - \left(\frac{V_t}{V_l} \right)^2 \right] = 0 \quad (3.2.12)$$

Of the six possible velocities, only one real value exists for materials for which Poisson's ratio μ lies in the range $0 < \mu < 0.5$:

$$V_r = \frac{0.87 + 1.13 \mu}{1 + \mu} V_t \quad (3.2.13)$$

Where V_r is the Rayleigh or surface wave velocity, μ the Poisson's ratio, $\mu = (1-2b^2)/(2-2b^2)$, $b = V_t/V_l$ (Szilard, 1982).

3.4.2 Attenuation of ultrasound

Attenuation of ultrasound as a function of incident frequency can provide the most significant information about the material characteristics. There are no really well-established methods of measuring the frequency dependent attenuation of ultrasound; however, some techniques are possible within the constraints of ultrasonic sources and analyzing instruments.

Pulse-echo technique

Pulse-echo systems are widely used for ultrasonic measurement of attenuation properties of a material. With this method at least two back surface echoes (reflections) from the specimen must be obtained. An important use of frequency spectrum analysis involves differential analysis of successive echoes arising from a single pulse. Each successive time domain echo will be more attenuated than its predecessor. The portion of the time domain signal that includes the first and second echoes are digitized and processed. Attenuation versus frequency is determined by a spectrum analysis of the first and the second echoes by means of Fourier transform. In the frequency domain the ratio of the amplitudes for a series of frequency components forms the basis for determining a functional relation between the attenuation coefficient and frequency, α vs f .

Through-transmission method

Through-transmission measurement of the attenuation coefficient for a material can be used when the material is very attenuative and the multiple back surface echoes from the specimen can not be obtained, as in the case of fruit and vegetable tissues. When ultrasonic waves are transmitted through the material, the total loss of the ultrasonic energy (including attenuation, reflection and coupling loss) can be expressed as follows:

$$T = 20 \log(A_0/A) \quad (3.2.14)$$

where

T = the total loss in dB,

A_0 = the amplitude of the transmitted energy without test material placed between the transducers,

A = the amplitude of the transmitted energy through the test material.

The loss due to attenuation is linearly dependent on the thickness of a given material, while the reflection loss and coupling loss is independent of the material thickness. Therefore the total loss T can also be represented as

$$T = \alpha x + R \quad (3.2.15)$$

where

α = the attenuation coefficient, dB/mm,

x = the thickness of the testing material, mm,

R = the reflection and coupling loss, dB.

The reflection and coupling loss for a given material and transducers is a constant. Therefore, the total losses of ultrasonic energy after travelling through two different known distances in the testing material are as follows:

$$T_1 = 20 \log(A_0 / A_1) = \alpha x_1 + R \quad (3.2.16)$$

and

$$T_2 = 20 \log(A_0 / A_2) = \alpha x_2 + R \quad (3.2.17)$$

where

T_1 = the total loss after travelling the distance x_1 ,

T_2 = the total loss after travelling the distance x_2 ,

A_1 = the signal amplitude received after travelling the distance x_1 ,

A_2 = the signal amplitude received after travelling the distance x_2 .

Subtracting Eq. (3.2.17) from (3.2.16) yeild

$$\alpha = \frac{20 \log(A_1 / A_2)}{x_1 - x_2} \quad (3.2.18)$$

Therefore, the attenuation coefficient for the material at the given frequency can be calculated directly from the amplitudes of transmitted ultrasonic waves through the testing material of two different thicknesses.

To determine the attenuation coefficient as a function of frequency, broadband ultrasonic waves are transmitted into the material and the transmitted ultrasonic signals are converted into their respective frequency components by Fast Fourier Transformation techniques. The frequency domain spectra of the two slice specimens of the testing material with different thicknesses are used to construct the functional relation between the attenuation coefficients and the frequencies for the material.

Another aspect of ultrasonic spectroscopy involves selective frequency absorption or transmission of wide-band ultrasound. Here, instead of measuring attenuation coefficient, the transmitted frequencies are measured. Such relations are not only significant in the determination of optimum frequency response of a material, they are also important in the characterization of materials. The aspects of ultrasonic spectroscopy need to be understood and developed further before reliability and confidence are established in their applications and interpretations.

4. TECHNION - I.I.T. AND A.R.O. REPORT

4.1 Preliminary Study of Fruit and Vegetable Properties by Ultrasonic Excitation (Objectives 1 & 2)

4.1.1 Experiment Setup

The experimental system was designed for determination of basic acoustic properties of fruit and vegetables, namely, velocity of wave propagation, wave attenuation and reflection. The basic setup included a high-power low-frequency ultrasonic instrument (Krautkramer Model USL 33) and transducers, an immersion water tank and a 66 Polyamide rod as a wave transmitter. The central frequencies of the transducers were 50 kHz and 500 kHz, with beam diameters of 55 mm and 45 mm, respectively. The output pulse was measured visually upon a built-in CRT monitor. A microprocessor-controlled serial interface allowed to transfer the digital read-out of echo amplitude, the instrument gain and the pulse transit time to an external microcomputer for further analysis.

4.1.2 Experimental Procedure

Cylindrical specimens of fresh tissue, 20 mm in diameter, were obtained by pushing a sharp tube through the intact fruit. The cylindrical specimens were then cut by a sampler guillotine to several specific lengths. Tests to determine the velocity wave propagation and attenuation coefficient for the specimens were carried out using the transmission mode of the ultrasonic instrument, as shown in Fig. 4.1.1.

Fig. 4.1.1: Transducer configuration for velocity and attenuation measurements. a - 50 kHz transmitter; b - 50 kHz receiver; c - Polyamide rod; d - fruit tissue spesimen

The Polyamide rod, 20 mm in diameter and 90 mm long, was attached to the center of the transmitter in order to achieve proper time delay between the transmitted and the echo pulses, and to eliminate echo created by pulse passing through air. Preliminary tests were carried out in order to find the pulse transmissibility of the Polyamide rod vs. gain setting.

Velocity measurements

The compressional (longitudinal) P waves are the fastest and hence the first to reach the receiver. The ultrasonic pulser-receiver instrument was used to determine the P wave velocity, C_p , by measuring the length of the specimen by the transit time of the pulse through the sample. Three lengths of fruit specimen (10, 15 and 20 mm) were tested. The transit time was obtained by taking a specific reference point on each pulse function. 23 readings were taken for each length, and a mean value of the transit time of the pulse was then determined.

Attenuation Measurements

Three kinds of fruits were checked for attenuation: potato, avocado and carrot. The attenuation characteristics of the materials were determined with the 50 kHz transducers and specimens of different length. For each transmitted pulse, the receiver output on the CRT screen was observed, and the relevant amplitude was selected and recorded. Again, 23 tests were conducted for each length of fruit specimen. Considering the decaying of the wave amplitude, the values of the attenuation coefficient for a material was determined by fitting a curve of the form of Eq. (3.2.5).

Reflection measurements

Tests for measuring the reflection properties of tissues were conducted using an immersion tank full of water. Pulse echo visualization techniques allowed to measure the amplitude of reflected waves (Robinson and Kossoff, 1978). The manufacturer of the ultrasonic probes did not recommend the use of 50 kHz probe in the pulse-echo mode, therefore a single 500 kHz transmitter-receiver transducer was used. The transmitter was mounted on a linear fixation device, positioned at the top of the immersion tank, in the water. At the opposite end of the tank a 40 mm diameter, 10 mm thick slice of each fruit was fixed to an aluminum plate, mounted on a second linear fixation device. The distance between the transducer and the sample faces was about 170 mm (the near field distance wave in water). A suitable display of the transmitted pulse was formed on the screen by adjusting the gain control on the USL33 unit, and values of the pulse amplitude and the gain setting for each sample was recorded.

The reflection coefficient, Γ , is defined by the following equation (Wells, 1969):

$$\Gamma = A_r / A_i \quad \dots\dots\dots (4.1.1)$$

where A_r is the amplitude of reflected signal and A_i - the amplitude of incident signal. The

reflection loss, β , in decibel (dB), is defined as follows (Wells, 1969):

$$\beta = 20 \log (A_i / A_r) \quad \dots\dots\dots (4.1.2)$$

This factor represents the inverse reflection ratio of the signals. For example, the reflection loss is 0.0 dB for a perfect reflector.

Reflection tests were performed with 23 samples of 8 different fruit and vegetable tissues. The reflection parameters for a material were determined by fitting a curve of the form of Eq. (4.1.1). Brass, Plexiglass and Aluminum samples were tested as well, for calibration and reference purposes. The reflection coefficient of brass was selected as a calibration means for the instrument. The measured reflected amplitude of brass was recorded and then divided by its coefficient of reflection taken from the literature (Wells, 1969), to give the full value of the incident amplitude of the instrument at a certain gain setting. This setting was kept constant throughout the reflection tests.

4.1.3 Results and Discussion

Wave Propagation Velocity

The compressional wave velocity for several fruit and vegetable specimens is given in Table 4.1.1. The sound velocity of air at standard conditions is also given for reference purposes.

Table 4.1.1 Compression wave velocity, C_p , for some fresh fruit and vegetable specimens (23 Samples each), and for Polyamide rod

Material	Mean velocity C_p (m/sec)	Std. dev.
Air	331.0	---
Avocado ("soft")	383.23	27.07
Potato	380.04	6.59
Cucumber (longitudinal)	371.82	4.46
Carrot (longitudinal)	341.13	15.47
Avocado ("hard")	273.55	16.50
Pumpkin	267.94	3.36
Melon	242.81	13.17
Apple	184.55	24.21
Polyamide rod	843.83	0.25

The velocity of sound in apples was found to be relatively low, which is in agreement with

previously reported values in apples using other measuring methods (Garrett and Furry, 1972). Lack of a clear fibrous structure and the large intercellular air spaces in apple tissue might be the reason for the low sound velocity. Potato tissue also does not have a clear fibrous structure, but only 2% of intercellular air spaces allow higher sound velocity. The carrot tissue was cut along its longitudinal axis, where a clear fibrous structure may cause the relatively high sound velocity.

The sound velocity for potato tissue was 380 m/s which was much lower than that obtained by Povey (1989). The difference might be due to the different variety and storage history. Two kinds of avocado tissue were tested: "soft" (ripe) avocado, and fresh "hard" avocado. The hard avocado has a relatively low sound velocity, while the soft one has a much high sound velocity. This clear finding indicates that sound velocity may be used for ripeness classification in avocado.

Attenuation properties

The attenuation measurements of some fruit and vegetable tissues were conducted using the Polyamide rod as a transmitter interface, as mentioned before. The response of the Polyamide rod itself to the gain setting of the instrument is shown in Fig. 4.1.2. Because of the low attenuation coefficient of the material, a gain point of 8 dB was the maximum setting value for the transmitted pulse. The linear regression output of five data points yielded the following equation:

$$\ln A_0 = 3.9779 + 0.10223 * G \quad \dots\dots\dots (4.1.3)$$

where A_0 is the calculated pulse amplitude and G is the gain setting in dB. The determination coefficient of the data points was $R^2 = 0.9995$. The low attenuation and the high determination coefficient achieved showed that the Polyamide rod may be used as a proper interface between the transmitter and the fruit specimen.

Wave amplitude, A_x , was plotted against path length, x , for potato, carrot and avocado tissues, as shown in Fig. 4.1.3. Linear regression of the data yielded the attenuation coefficients for the tested fruit [Eqn. (4)], as given in Table 4.1.2.

Table 4.1.2 Attenuation coefficients for fresh potato, carrot and avocado tissues at 50 KHz

Sample	No. of samples	Linear regression output			Attenuation - α	
		$\ln A_0$	x coeff.	R square	(neper/mm)	(dB/mm)
Potato	7	-0.01389	-0.08748	0.91392	0.08748	0.75989
Carrot	7	-1.77971	-0.07259	0.82006	0.07259	0.63053
Avocado	5	-1.70243	-0.18401	0.97949	0.18401	1.59835

Note the wavy fluctuation around the regression line which may be attributed to the different length of the samples.

Fig. 4.1.2: Gain setting of pulse amplitude for Polyamide rod calibration at 50 kHz

Fig. 4.1.2: Normalized wave amplitude vs. path length for attenuation determination at 50 kHz

Reflection losses

Measurements of the pulse amplitude reflected from the tissue surface allow determination of the reflection coefficient and reflection loss of the material immersed in water, according to Eqs. (4.1.1) and (4.1.2). The data measured also gave the amount of signal left to be transmitted through the specimen. Measured results of reflection coefficient and calculated reflection loss for some fruit and vegetable specimens are given in Table 4.1.3. For verification of the calculation method, the reflection properties of Plexiglass and aluminum were also calculated. The results (Table 4.1.3) were very close to those reported by Wells (1969): 8.7 dB for Plexiglass and 1.4 dB for aluminum. The discrepancy between the measured and the cited results can be attributed to variation in material properties and experimental error of the measuring system.

Apple tissue immersed in water gave a very high reflection coefficient which means that a very small fraction of the incident pulse penetrated the material. Similar results were reported by Upchurch (1985). On the other hand, results obtained with potato tissue showed relatively small reflection coefficients which left a substantial portion of the incident pulse to be transmitted into the potato tissue. All reflection tests were performed using the method of immersion in water. It seems that due to the large reflection loss for some products, a medium other than water should be selected as a couplant for reducing the mismatch with the material tissue.

Table 4.1.3. Reflection loss in water for some fresh fruit and vegetable tissues and some other materials at 500 KHz

Material	Mean Ar (% screen)	Std. dev.	<u>Reflection - β</u>	
			Loss(dB)	Coeff.
Apple	130.11	0.245	0.12	0.98643
Avocado (hard)	113.70	0.212	1.34	0.85743
Avocado (soft)	85.88	0.331	3.61	0.66013
Pumpkin	116.16	0.405	1.11	0.88013
Melon	94.33	0.471	2.94	0.71323
Carrot	46.51	0.226	9.14	0.34903
Cucumber	57.85	0.363	7.13	0.44013
Potato	45.01	0.231	9.33	0.34143
Plexiglass	44.14	0.112	9.53	0.33383
Aluminum	112.03	0.341	1.41	0.84983

4.1.4 Summary and Conclusions of the Preliminary Study

A preliminary experimental investigation of fruit and vegetable tissues demonstrated the feasibility of ultrasonic excitation for testing of agricultural products. Analysis of the results led to the following conclusions:

1. Within the frequency range of 50 kHz and 500 kHz and high power excitation amplitude, it was possible to determine the basic acoustic properties of the tested fruits and vegetables by ultrasonic excitation;
2. Wave propagation velocities in the tested products were measured to be between 180 and 380 m/Sec. Changes in sound velocity may be used for ripeness classification in some products.
3. Attenuation coefficients of fruit and vegetables were found to be relatively high. However, in a frequency of 50 kHz it was possible to achieve significant penetration level into the material and to measure relatively low attenuation coefficients of 0.64 dB/mm and up to 1.59 dB/mm in some fresh fruit and vegetable tissues.

The preliminary study of this chapter was summarized in the paper "Determination of Fruit and Vegetable properties by Ultrasonic Excitation" (Chapter 8 of this report).

4.2 Systematic Testing of Acoustical, Mechanical and Quality Parameters of Melon Tissue

The winter-grown melon (*Cucumis melo* L., cv 'Galia') in Israel is particularly prone to 'internal breakdown'. This physiological disorder is characterized by excessive tissue softening beginning in the seed cavity, ultimately resulting in the breakdown of the entire fruit. Autumn-grown fruits were free of internal breakdown. The precise factors governing this condition are unknown; however, they are thought to be attributed to overripening of the fruit flesh. As this occurs - even while the external peel remains green or light yellow - the disorder is undetectable without first cutting open the melon. Afflicted melons, included accidentally within export shipments, can burst in transit, showering all surrounding fruits with their contents, and thereby becoming a rich source of fungal pathogens.

The physiology of melon fruit softening has been investigated previously (Bianco and Pratt, 1977; Pratt et al., 1977; Lester and Dunlap, 1985); however, the relationship between fruit softening and changes in cell wall components remains elusive. The urgency of this issue has triggered a multi-disciplinary effort to find a solution. The use of non-destructive means to detect internal breakdown of fruits was suggested by Ben-Zioni (1986). X-ray, infrared, and ultrasonic methods were tested. No clear evidence of breakdown detection by any of these methods has been presented; however, researchers claim that the ultrasonic method is the most promising. The present study examines quality and ultrasonic parameters of different flesh areas of melons, to provide basic physiological information on ripening. In addition, basic mechanical properties of the melon tissue will be tested as well.

4.2.1 Materials and Method

'Galia' melons were harvested during the autumn and winter of 1988-1989 in the northern Arava Valley of Israel. Autumn-grown fruits were harvested at degrees '2' (green) and '3' (ripe) on a scale of peel coloration, in which '2' was turning-yellow green and '3' was fully yellow. In addition, ripe fruits were stored for 10 days at 8°C until a degree '4' peel color (overripe) was attained. Winter-grown fruits were harvested and analyzed at degree '3' (ripe) only. Firmness of whole fruits was measured using a Chatillon durometer. The compression force required to puncture the rind of non-peeled fruit was measured using a 6.35 mm - diameter plunger at a 3 mm/s loading rate. Each fruit was then split in two: one half for mechanical and ultrasound testing, and one half for standard quality and structural tests. In both cases, flesh was sampled from three depths: next to the seed cavity (inner), the center of the flesh (middle), and next to the peel (outer). In the cases of mechanical and ultrasonic properties tests, cylindrical specimens of fresh tissue, 20 mm in diameter, were obtained by pushing a sharp tube through the melon flesh, perpendicular to its surface. Each cylinder was cut into three sections using a sampler guillotine. Each section was cut into 10 mm length specimens to represent the outer, central and inner parts of the melon flesh.

Acoustical Properties Determination

Tests to determine the velocity wave propagation, C_p , and attenuation coefficient, α , for the specimens, were carried out using through transmission mode. A 50 kHz transmitter and 50 kHz receiver were coupled to both sides of the specimen with a thin film of mechanical grease. An AKULON rod, 20 mm in diameter and 90 mm long, was attached to the center of the transmitter in order to achieve proper time delay between the transmitted and the echo pulses, and to eliminate the echocreated by pulse passing through air.

The propagation velocity of the acoustic wave in the material was obtained by measuring the time required for the pulse to transverse the sample, taking a specific reference point on each pulse function. 20 runs were conducted for each length. The compressional wave propagation velocity, C_p , was determine by the expression $C_p = L / T$, where L is the slice length and T is the transit time.

The attenuation characteristics of the melon tissue was determined with the 50 kHz transducers and specimens of 10 mm in thick. For each transmitted pulse, the receiver output on the CRT screen was observed, and the relevant amplitude was selected and recorded. Again, 20 runs were conducted for each length of fruit specimen, to obtain the amplitudes of the decaying ultrasonic wave.

Mechanical Properties Determination

An Instron Universal Testing Machine was used to perform compression tests between parallel flat plats on melon fruit and find the elastic and tangent modulus of the specimens. The fruit was mounted in the center of the two parallel flat plates. Each specimen was placed on a 0 - 50 N

compression load cell and compressed at a rate of 50 mm per minute. A synchronously driven strip chart recorded the force deformation curve for the tissue. Since the load, cross-head and chart speed of the machine were known, it was possible to use standard formulas for the determination of the modulus of elasticity and the tangent modulus of the melon fruit.

Determination of Quality Parameters

Fruit samples were tested for total soluble solids (TSS) and percent moisture, dry basis (DW) tests (Horwitz, 1970). TSS was measured with a refractometer, and samples for %DW measurement were dried in a 60°C oven for 3 days prior to reweighing.

4.2.2 Results and Discussion

Modulus of Elasticity and Tangent Modulus

Typical stress-strain curves for the fruit specimens taken from three sections, namely, the outer, middle and inner parts of the winter ripe melons are shown in Fig. 4.2.1. Within the range of 0 to 20 N tested, the outer specimen had compression curves that are practically linear, as illustrated in the figure. The inner specimen compression curve consisted of two linear portions of different inclinations. The middle section usually had a curve similar to the inner section. However, sometimes the curve has only one linear section similar to the outer curve. In this case it is possible that the second portion of different inclination existed out of the maximum compression range applied. This kind of stress-strain relationship is common in various materials (Byars et al., 1983).

Fig. 4.2.1: Typical stress-strain curves for outer, middle and inner part of the melon

The initial linear portion of all three curves was determined using the relationship between stress and strain (Hook's law). For uniaxial state of stresses not greater than the proportional limit, the modulus of elasticity, E_0 , was easily obtained:

$$E_0 = \sigma / \varepsilon \quad (\sigma \leq \sigma_{PL}) \quad \dots\dots\dots (4.2.1)$$

where σ = stress, ε = strain, σ_{PL} = stress at the proportional limit.

A second parameter for the inner curves was the tangent modulus, denoted by E_T , which is the slope of the stress-strain curve at any point beyond the proportional limit ($\sigma > \sigma_{PL}$):

$$E_T = (\sigma - \sigma_{PL}) / (\varepsilon - \varepsilon_{PL}) \quad (\sigma > \sigma_{PL}) \quad \dots\dots\dots (4.2.2)$$

where ε_{PL} = strain at the proportional limit.

The values of σ_{PL} and ε_{PL} were measured directly from the curves and used in equations (4.2.2) and (4.2.3). Tables 4.2.1 and 4.2.2 give the mean and standard deviation values of the parameters E_0 and E_T for the three sections (inner, middle and outer) of winter- and autumn-grown melons, respectively. The results obtained show that the modulus of elasticity and the tangent modulus systematically decreased with deeper section in the fruit tissue. For the same section tested, the tangent modulus was always smaller than the modulus of elasticity. Moreover, the tangent modulus decreased with the tissue depth faster than the modulus of elasticity. These findings of the winter melons (Table 4.2.1) were similar to that of the autumn-grown melons (Table 4.2.2).

Wave Propagation Velocity and Attenuation Properties

The compression wave velocity, C_p , and the attenuation coefficient, α , for three sectional specimens of winter- and autumn-grown melons tested are also given in the Tables 4.2.1 and 4.2.2. The calculated values of wave propagation velocity were slightly reduced with slice depth of the three sections, but not significantly, contrary to expectations. The standard deviation increased greatly with the depth, especially in the inner section. This high diversion of results may be attributed to the varying ripeness of the inner slice. This finding also indicates that wave propagation velocity may not be useful as a predictor of ripe melon properties. The attenuation tests were conducted using the AKULON rod mentioned previously. It can be seen in that the attenuation coefficient α of ripe winter melons strongly increased with the depth of the sample. These definite changes of the attenuation coefficient with slice depth and fruit ripeness in the winter melons indicate a potential use of this acoustic parameter for mechanical properties or quality detection.

Table 4.2.1 Acoustical, mechanical and quality parameters of ripe winter-grown melons in three depth sectors (3 specimens for each depth sector for each one of 15 melons)

Parameters		Slice		
		Outer	Middle	Inner
Depth	(mm)	10	20	30
E ₀	(kPa)	644.16 (129.58)*	437.39 (88.31)	208.64 (70.90)
E _T	(kPa)	632.04 (138.08)	229.31 (66.71)	33.30 (35.94)
C _P	(m/s)	90.49 (12.19)	78.57 (33.47)	87.24
α	(dB/mm)	3.71 (0.88)	5.21 (0.97)	7.09 (0.82)
TSS	(%)	9.34 (0.94)	11.42 (1.48)	12.99
DW	(%)	10.60 (0.57)	13.09 (1.06)	14.41
Puncture force	(N)	6.16 (0.95)	-	-

* The bracketed figures are the standard deviation.

Quality Tests

The melon fruits were of high quality both in appearance and flavor. The flesh of the winter-grown fruits, however, while being exceptionally sweet, was slightly overripe in texture and showing the beginning of internal breakdown around the seed cavity. This was despite the yellow green coloration of the peel which suggested a less advanced stage of ripening. Green fruits gave the lowest TSS readings, while overripe fruit readings were highest. In addition, green fruits had the narrowest TSS range between the outer and inner flesh (4.63 to 5.59%, respectively). The TSS content of the fruits rose as the season progressed, to a high of about 13%, as recorded around the seed cavities of ripe, winter-grown fruits (Tables 4.2.1 and 4.2.2).

The TSS distribution within the winter fruits (Table 4.2.1) shows an increasing gradient toward the center of the fruit, from 9.34% at the outer slice a high value of 12.99% as recorded around the seed cavities of the ripe winter-grown fruits. Such a TSS gradient was first recorded by Scott and MacGillivray (1940) and has been shown to be closely correlated with an increase in sucrose levels

in the developing fruit. A closely similar pattern to that of the TSS was observed for the DW. The TSS and DW distribution within the autumn-grown fruits (Table 4.2.2) show the same tendency, but less definite than in the winter-grown melons, which were exceptionally sweet. Firmness of the whole fruits were also measured for reference purposes (Tables 4.2.1 and 4.2.2).

Table 4.2.2 Acoustical, mechanical and quality parameters of green, ripe and overripe autumn-grown melons in three depth sectors (3 specimens for each depth sector for each one of 15 melons)

Parameters	Green			Ripe			Overripe		
	Outer	Middle	Inner	Outer	Middle	Inner	Outer	Middle	Inner
Depth (mm)	10	20	30	10	20	30	10	20	30
E_0 (kPa)	912.6 (129.4)**	747.6 (181.5)	449.8 (110.9)	-	-	-	651.0 (195.1)	448.8 (108.3)	231.7 (80.4)
E_T (kPa)	904.4 (151.6)	689.6 (218.7)	384.5 (201.4)	-	-	-	651.0 (195.1)	214.2 (112.2)	50.5 (56.1)
C_p (m/s)	68.6 (19.4)	61.4 (16.7)	66.0 (14.3)	-	-	-	81.7 (10.8)	73.9 (10.1)	71.4 (2.8)
α (dB/mm)	2.66 (0.11)	2.82 (0.26)	2.89 (0.28)	-	-	-	5.48 (0.89)	6.06 (1.20)	7.04 (0.70)
TSS (%)	4.63 (0.56)	5.05 (0.61)	5.59 (0.80)	6.07 (0.65)	7.29 (0.99)	8.29 (1.15)	6.60 (0.78)	7.96 (0.85)	9.09 (1.00)
DW (%)	4.85 (0.45)	4.91 (0.43)	5.49 (0.58)	5.94 (0.16)	7.53 (0.23)	8.60 (0.26)	6.42 (0.67)	8.16 (0.74)	7.18 (1.21)
Puncture force (N)	9.85 (2.08)	-	-	6.15 (0.43)	-	-	3.49 (0.55)	-	-

* Each result is the mean of 15 fruits.

** Bracketed figures are standard deviation.

Statistical Analysis

All available mechanical, acoustical and quality parameters of the winter- and autumn-grown fruit samples, as well as the sectoral sample depth, were analyzed using the statistical analysis system SAS. The correlation output of the winter-grown melons (Table 4.2.1) is shown in Tables 4.2.3. High correlation was found between the depth parameter x and the mechanical modulus (0.8785) and between the depth parameter x and the acoustical attenuation coefficient (0.8423). Relatively high correlation was found also between the elastic modulus and the attenuation coefficient (0.8440) and between the module of elasticity and the tangent modulus (0.8098) as well. However, very poor

correlation was found between the wave velocity propagation and the other parameters.

Table 4.2.3 Correlation coefficient and probabilities for acoustical and mechanical properties of ripe winter-grown melons (Number of observations is 135)

Parameters	x	E ₀	E _T	α	C _p	TSS	DW	Punc. Force
x	1.00000 0.0000*	-0.8785 0.0001	-0.9216 0.0001	0.8423 0.0001	-0.0551 0.5254	0.7614 0.0001	0.8936 0.0001	0.0000 1.0000
E ₀	-0.8785 0.0001	1.0000 0.0000	0.8098 0.0001	-0.8440 0.0001	0.0399 0.6457	-0.6758 0.0001	-0.7899 0.0001	0.2845 1.0000
E _T	-0.8845 0.0001	0.8098 0.0001	1.0000 0.0000	-0.7885 0.0001	-0.0818 0.4385	-0.6689 0.0001	-0.8644 0.0001	0.1842 0.5110
α	0.8424 0.0001	-0.8440 0.0001	-0.7885 0.0001	1.0000 0.0000	-0.0570 0.5117	0.6101 0.0001	0.7870 0.0001	-0.4910 0.0631
C _p	-0.0551 0.5254	0.0399 0.6456	-0.0818 0.1036	-0.0570 0.5115	1.0000 0.0000	-0.0548 0.7208	-0.0271 0.8614	0.4323 0.1075
TSS	0.7614 0.0001	-0.6798 0.0001	-0.6689 0.0001	0.6101 0.0001	-0.0548 0.7208	1.0000 0.0000	0.7736 0.0001	-0.0531 0.8509
DW	0.8936 0.0001	-0.7859 0.0001	-0.8644 0.0001	0.7870 0.0001	-0.0271 0.8614	0.7360 0.0001	1.0000 0.0000	0.2234 0.4023
Punc. Force	0.0000 1.0000	0.2950 0.3032	0.1842 0.5110	-0.4910 0.0631	0.4323 0.1075	-0.0531 0.8509	0.2334 0.4023	1.0000 0.0000

* Probability

The high correlations obtained between the mechanical and the attenuation parameters of the winter-grown melons suggested that mathematical expression could be obtained for these variables. The GLM procedure of SAS was used in order to find a proper equation for the modulus of elasticity (E₀) and the tangent modulus (E_T), as affected by the attenuation coefficient, α_(x), and the slice depth, x. The selected empiricel equations for the tested population were:

$$E_0(x) = 1114.5 - 14.01 x - 11.113 \alpha_{(x)} + 0.606 \alpha_{(x)}^2 \dots\dots\dots (4.2.4)$$

$$E_T(x) = 961.5 - 14.756 x - 12.994 \alpha_{(x)} + 0.855 \alpha_{(x)}^2 \dots\dots\dots (4.2.5)$$

In this equation, linear relation of the mechanical parameters with slice location and quadratic relation with attenuation coefficient were assumed. The determination coefficients of the E₀ and E_T curves

were found to be $R^2 = 0.814$ and $R^2 = 0.832$, respectively. These relatively high determination coefficients may suggest that, after validation of this type of equations with melons of different ripeness degrees, a prediction equation for internal fruit properties could be evaluated by measurements of some acoustic parameters at the outer layer of the fruit.

The correlation output of the overripe autumn-grown melons (Table 4.2.2) is shown in Table 4.2.4. Fairly good correlation was found between the depth parameter x and the mechanical modulus (0.7844) and the TSS, and between the module of elasticity and the tangent modulus (0.9055) as well. However, poor correlation was found between the acoustical parameters and all other parameters. Similar correlations of the green autumn-grown melons did not improve the results.

Correlative increases in TSS and DW with increasing ripeness and sugar content, as observed in the present study, have been well documented (Bianco and Pratt, 1977; Lester and Dunlap, 1985), although their gradients within the fruits themselves have not been explored previously. Both parameters agree with the greater sweetness of the inner versus the outer fruit flesh. Very high TSS levels in winter-grown fruits are interesting, prompting the question whether they are, in any way, linked to the internal breakdown disorder. The decrease in fruit firmness with ripening is also a well-known phenomenon, and the three parameters together provide a useful standard of ripening, as well as the onset of internal breakdown.

The radial distribution of the quality parameters especially in TSS and DW are similar in nature to the acoustical parameters. The acoustical attenuation of a transmitted pulse drastically increased with the depth of the fruit sample, from a value of 2.66 dB/mm in outer specimens of green autumn fruit up to 7.09 dB/mm in inner specimens of the ripe fruits. The dependence on depth, especially in the winter-grown melons ($R=0.842$) indicated the potential use of the attenuation coefficient to predict internal fruit properties, suggesting that acoustical measurements may non-destructively predict internal fruit quality and breakdown phenomena around the seed cavity.

Puncture force of whole fruits decreased with increasing ripeness from a high of 9.85 N in green fruits to lows of 3.49 N in overripe, autumn-grown fruits (Table 4.2.2) in winter-grown fruits (Table 1). However, unsatisfactory correlation was found between the puncture force and the other parameters of the outer fruit segments.

Table 4.2.4 Correlation coefficient and probabilities for acoustical and mechanical properties of overripe autumn-grown melons (Number of observations is 126)

Parameters	x	E ₀	E _T	α	C _P	TSS	DW	Punc. Force
x	1.00000 0.0000*	-0.7844 0.0001	-0.8498 0.0001	0.5569 0.0001	-0.3010 0.0006	0.7659 0.0001	0.2849 0.0710	0.0000 1.0000
E ₀	-0.7844 0.0001	1.0000 0.0000	0.9055 0.0001	-0.5543 0.0001	0.2145 0.0159	-0.6087 0.0001	-0.1969 0.2172	0.2672 0.3557
E _T	-0.8498 0.0001	0.9055 0.0001	1.0000 0.0000	-0.5274 0.0001	-0.3671 0.0001	-0.6539 0.0001	-0.4248 0.0079	0.2672 0.3557
α	0.5569 0.0001	-0.5543 0.0001	-0.5274 0.0001	1.0000 0.0000	-0.1813 0.0422	0.2005 0.2029	-0.0269 0.8675	-0.5115 0.0615
C _P	-0.3010 0.5254	0.2145 0.0159	0.3671 0.0001	-0.1813 0.0422	1.0000 0.0000	-0.4382 0.0037	-0.2437 0.1246	0.7763 0.0011
TSS	0.7659 0.0001	-0.6087 0.0001	-0.6539 0.0001	0.2005 0.2029	-0.4382 0.0037	1.0000 0.0000	0.3620 0.0200	-0.1784 0.5418
DW	0.2849 0.0710	-0.1969 0.2172	-0.4248 0.0079	-0.0269 0.8675	-0.2437 0.1246	0.3620 0.0200	1.0000 0.0000	0.0297 0.9198
Punc. Force	0.0000 1.0000	0.2672 0.3557	0.2672 0.3557	-0.5115 0.0615	0.7763 0.0011	-0.1784 0.5418	0.0297 0.9198	1.0000 0.0000

* Probability

4.2.3 Summary and Conclusions of Systematic Testing of Melon Tissue

Acoustical, mechanical and physiological parameters of ripe winter melons were tested at different depths, and the relationships among them were analyzed. The test results of the winter-grown melons can be summarized as follows:

1. No significant changes were detected in wave propagation velocity through melon tissues of different depths. The dispersion of results was relatively high and widely expanded with the depth of the sample. These findings showed that sound velocity may not be used as a measure for internal properties distribution in ripe melons.
2. The acoustical attenuation of a transmitted pulse strongly increased with the depth of the fruit sample, from a value of 3.71 dB/mm in the outer specimens to 7.09 dB/mm in the inner specimens. This strong dependence on depth ($R=0.842$) indicated a potential use of the attenuation coefficient for the identification of internal fruit properties.
3. The modulus of elasticity, and especially the tangent modulus of the sample tissues, decreased drastically with the sample depth, from 644 and 342 kPa in the outer specimens to 209 and 33 kPa in the inner specimens, respectively.
4. Equations were established for the calculation of the modulus of elasticity and the tangent modulus of the melons as a function of tissue depth and attenuation coefficient. These equations showed good agreement with the data set ($R^2=0.814$ and $R^2=0.832$, respectively).
5. The quality characteristics tested in this study, namely, the percent of total soluble solids and the dry weight percent, both increased with fruit depth: from about 10% in the outer specimens up to 14% and more in the inner specimens. This suggests that mechanical or acoustical measurements, which had shown similar strong relationship with depth, may predict internal fruit quality.

Results of the work with autumn-grown melons supported the findings of the winter melons. However, the correlation coefficients between the related fruit parameters in the autumn melons (without internal breakdown) were significantly lower than those of the winter melons (with internal breakdown).

The work which started with winter melons was summarized in the paper "Acoustical, mechanical and quality parameters of melon tissue" (Chapter 8 of this report). A second paper, entitled "Evaluation of some ripening parameters of autumn- and winter-grown 'GALIA' melons", included the results of the two seasons and summarized the ultrasonic and quality testing of melon tissue (see Chapter 8 of this report).

4.3 Half-Cut Fruit Response to Ultrasonic Excitation (Objective 3)

As fruit and vegetable tissues are highly attenuated materials, the ultrasonic signals become undetectable after reaching a relatively shallow depth; hence, unlike in medicine and industry, it is almost impossible to use the pulse-echo method for deep defect detection. Furthermore, the use of low ultrasonic excitation frequencies (less than 100 kHz) does not permit sharply collimated sound beams. A probe contact face, which is only of the order of magnitude of the wavelength, may radiate also wave modes other than longitudinal waves. As a result, strong Rayleigh waves and disturbing echoes may develop in lightly damped materials, rendering the echo method practically unusable. However, when highly damped materials are used, these reverberations are practically avoided. Hence, the highly attenuating nature of fruit tissues may still allow the detection of local defects in the vicinity of the measuring points. In the present chapter, the directional characteristic of ultrasonic waves over the half-cut fruit tissue surface are studied in order to find a specific wave form, wave propagation path and sound pressure field, with the ultimate goal of employing the ultrasonic excitation technique for non-destructive whole fruit diagnosis.

4.3.1 Theoretical Considerations

Sound pressure fields in a half space material domain are analyzed commonly by the solution of the angular distribution of an acoustic pressure caused by a circular piston in fluid media (Krautkramer and Krautkramer, 1990):

$$P(r, \theta) = 2P(r, 0) J_1(\beta \sin\theta) / (\beta \sin\theta) \quad (4.3.1)$$

where

$$\beta = \pi (D / \lambda) \quad (4.3.2)$$

Here, $J_1(X)$ represents a Bessel function of the first kind, $P(r, \theta)$ is the directional acoustic pressure inside the material, $P(r, 0)$ is the pressure amplitude along the axis of symmetry, D is the diameter of the piston, r and θ represent the distance and angle of wave propagation and λ is the radiated wavelength. β is the the directivity parameter, where

$$2J_1(\beta \sin\theta) / (\beta \sin\theta) = 1 \quad (\theta = 0) \quad (4.3.3)$$

A more explicit expression of $P(r, 0)$ in Eq. (4.3.1), following Kinsler and Frey (1962), is:

$$P(r, 0) = \rho_0 \pi D^2 f U_0 / 8r = \rho_0 \pi 2 D^2 f^2 A_0 / 4r \quad (4.3.4)$$

where ρ_0 is the material density, f - frequency of the oscillator, U_0 and A_0 - the velocity and displacement amplitude of the oscillator, respectively. We will add a damping coefficient α to the classical model of Eq. 4.3.1 as follows:

$$P(r, \theta, \alpha) = 2P_0 (r_0/r) e^{-\alpha(r-r_0)} J_1(\beta \sin\theta) / (\beta \sin\theta) \quad (4.3.5)$$

where P_0 is the sound pressure amplitude at a distance r_0 along the axis of symmetry.

Referring back to Eq. (4.3.2), the directional sound pressure beam depends on the ratio D/λ . For $(D/\lambda) > 1$, the divergence of the beam angle is small and the beam has mostly a longitudinal nature. Then, the description of the sound field has a classic pressure distribution with a long central beam and small side lobes. With decreasing D/λ , the angle of divergence increases up to 90° , remaining constant thereafter (Krautkramer and Krautkramer, 1990). For a very small source, namely a point-source transmitter $[(D/\lambda) \ll 1]$, the pressure field has a nearly spherical characteristic for the longitudinal waves, and additional off-axis transverse waves with two large lobes on each side of the axis (Roderick, 1950; Filipczynski, 1963). As both the wavelength, λ , and the diameter of the oscillator, D , depend on the material tested and the characteristics of the transmitter, it is possible to determine the appropriate transmitter for the required directional wave propagation within the material. This classic solution for a fluid model will help understand and analyze the more complicated case of wave propagation in fruit tissue.

4.3.2 Experimental Setup and Test Procedure

The experimental setup (Fig. 4.3.1) included the low-frequency, high-power ultrasonic device and transducers, X-Y-Z linear fixation device and two Plexiglas exponential ultrasonic concentrators (after Makarov, 1964). The two ultrasonic concentrators were fixed to the flat circular oscillator of the transducers. The central frequency of the transducers' broadband was 50 kHz; the oscillator diameter of 55 mm was reduced to 6 mm at the concentrator end. The desired analog output pulse was selected manually on the built-in CRT monitor, digitized by a microprocessor-controlled serial interface, and transferred to an external microcomputer for further analysis.

Three kinds of fresh fruit were examined for directional characteristics: melon (*Cucumis melo* L., cv. "Galia"), avocado (*Persea Americana* Mill., cv. "Ettinger"), and potato (*Solanum tuberosum* L., cv. "Draga"). The fruits were split into two halves. One half-cut fruit was placed in a gypsum casting with the longitudinal fruit plane section faced upward for fixation purposes. The casting was mounted on an adjustable-height jack. Tests to determine the acoustic parameters and the directional characteristics of wave propagation were carried out by applying the transmission mode, using the experimental setup (Fig. 4.3.1). The transmitter (a) was mounted on a linear fixation device (b) and

attached with ultrasonic gel to the side of the fruit (c), placed in a gypsum casting (d). The center of the transmitter concentrator (e) was located 3 mm below the cut fruit surface, along its main axis. The receiver (f) was mounted on an X-Y-Z linear fixation device (g), perpendicular to the fruit plane section and the transmitter, as shown in the figure.

Data was collected and analyzed using two alternative coordinate systems: a cartesian system for three-dimensional pressure field presentation, and a polar coordinate system for a directional description of sound pressure amplitudes. Measurements were taken twice: once for the X-Y grid, and once for the angular R- θ display. The $r - \theta$ measurements were taken on a semi-circle of constant radius from the radiator source, and the pressure amplitudes were plotted as radius vectors from the center of the radiator. This method is capable of giving a good picture of the far-field directional orientation of the wave within the tissue.

Fig. 4.3.1 -- The experimental system for half-cut fruit testing: (a) transmitter; (b) linear fixation device; (c) half-cut fruit; (d) a gypsum casting; (e) energy concentrator; (f) receiver; (g) linear fixation device.

4.3.3 Results and discussion

Read-out presentation of the spatial distribution of the pressure amplitude over the half-cut fruit surface was made possible by 3-D graphical analysis software¹. Typical three-dimensional illustrations of the acoustic pressure field over avocado, potato and melon cut surfaces are shown in Figs. 4.3.2, 4.3.3 and 4.3.4, respectively. The figures indicate that the pressure amplitude decreases with increasing distance from the ultrasonic oscillator in all directions over the cut surface plane.

The decay rate of the pressure amplitude, depicted from the chart, yields the apparent directional attenuation in the fruit tissue. The apparent attenuation in the half-cut fruit includes two terms: a geometrical dispersion term, which is proportional to the inverse of the distance from the source of the wave energy, and an exponential term of the internal energy dissipation (Eq. 4.3.5). The apparent attenuation along the longitudinal and latitudinal axes for each of the tested half-cut fruits are summarized in Table 4.3.1.

Table 4.3.1 Apparent directional attenuation for fresh half-cut potato, avocado, and melon fruits along the principal axes

Fruit	<u>Longitudinal axis</u>		<u>Latitudinal axis</u>		Attenuation axes' ratio
	Attenuation (dB/mm)	R ²	Attenuation (dB/mm)	R ²	
Avocado	2.290	0.995	3.451	0.978	1.51
Potato	0.998	0.844	1.176	0.982	1.18
Melon	4.575	0.931	2.569	0.971	0.56

The directional attenuation for potato and avocado along the latitudinal axis was found to be higher than the decay rate along the longitudinal axis, denoted by attenuation ratios of 1.51 and 1.18 between the two directions, respectively. In contrast, this ratio was much lower for melon (0.56), which showed quite different directional decay (Fig. 4.3.4).

Near field pressure peaks on the longitudinal axis can be observed in the potato 3-D presentation (Fig. 4.3.3). Some other peaks that are observed over the cut surface may lead to questions regarding the nature of wave propagation in the fruits. This phenomenon was much more pronounced in melons (Fig. 4.3.4), and was practically nonexistent in the avocado tissue (Fig. 4.3.2).

The directional characteristics of pressure fields in avocado, potato, and melon are shown in Figs. 4.3.5, 4.3.6, and 4.3.7, respectively. The data were measured at a constant radius of 25 mm from the origin in avocado and potato, and 10 mm in melon. The pressure amplitude is presented in the figures as a percentage of the maximum amplitude measured at each test. The constant distance from the wave source and the relative amplitude eliminate damping effects and reveal the directional

¹ GRAFTOOL - Graphical Analysis System. 1990. 3-D Visions Corporation, Redondo Beach, CA 90277, USA

dispersion characteristics in each fruit.

The directional characteristics in avocado (Fig. 4.3.5) demonstrate features similar to the classical pressure amplitude distribution in fluids, with a long central beam of high amplitude and small side lobes. A similar picture was obtained for potato at data points of the same distance from the origin (Fig. 4.3.6). Conversely, a totally different picture was obtained within the half-cut melon (Fig. 4.3.7): maximum pressure amplitudes were obtained on both sides of the central (90°) axis, while the frontal wave amplitude was measured as only 45% of the maximum pressure amplitude.

Fig. 4.3.2: Sound pressure field over the surface of a half-cut avocado at 50 kHz excitation frequency, oscillator diameter $D = 6$ mm

Fig. 4.3.3: Sound pressure field over the surface of a half-cut potato at 50 kHz excitation frequency, oscillator diameter $D = 6$ mm

Fig. 4.3.4: Sound pressure field over the surface of a half-cut melon at 50 kHz excitation frequency, oscillator diameter $D = 6$ mm

Fig. 4.3.5: Directivity diagram of pressure field over the surface of a half-cut avocado at 50 kHz excitation frequency, $D = 6$ mm, $r = 25$ mm

Fig. 4.3.6: Directivity diagram of pressure field over the surface of a half-cut potato at 50 kHz excitation frequency, $D = 6$ mm, $r = 25$ mm

An attempt was made to use the theoretical equation of the fluid model - Eq. (4.3.5) - to represent the ultrasonic pressure field of half-cut avocado and potato (Figs. 4.3.2 and 4.3.3). A MATLAB² curve fitting subroutine of Nelder-Mead simplex algorithm was used for the solution of the unknown parameters P_0 , α and β of the nonlinear equation, where r_0 , r , θ and the measured pressure amplitude P were known. The results obtained for avocado and potato are presented in Table 4.3.2 and Figs. 4.3.8 and 4.3.9, respectively. High correlation coefficients were obtained between the fitted lines and the data sets, despite the obvious difference between the fruit tissue and the assumed fluid model.

Table 4.3.2 Wave pressure field parameters for half-cut avocado and potato (Eq. 4.3.5) at 50 kHz excitation frequency, $D = 6$ mm, $r_0 = 25$ mm

Fruit	Wave pressure P_0 (N/m ²)	Attenuation α (dB/mm)	Bessel parameter β	Coefficient of determination	Velocity (m/sec)
Avocado	2.053	1.598	2.168	0.9773	306
Potato	4.819	0.525	1.050	0.8625	748

The velocities of wave propagation were calculated using the recorded flight-time of the wave; the direct calculation yielded velocities of 306 m/sec for avocado and 784 m/sec for potato ($R^2=0.7876$ and $R^2=0.6680$, respectively), as shown in the table. These wave velocities are lower than the velocities which could be calculated by the fluid model (Eq. 3.4.2) and a piston of 6 mm diameter.

Recalculation of the wave pressure field over the surface of the half-cut avocado of Fig. 4.3.2 is demonstrate in polar coordinates in Fig 4.3.10. Equation (4.3.5) and the avocado parameters of Table 4.3.2 were used for the calculation. An attempt to apply Eq. (4.3.5) as a wave pressure model for half-cut melon has failed. Yet, the wide angle of ultrasonic wave propagation in melons may be useful for inclined beam testing of fruit properties and local defects in the vicinity of the transducers.

4.3.4 Summary and Conclusions

The sound pressure field of ultrasonic waves developed over the half-cut fruit surface was examined. The wave propagation behavior and the directional characteristics of some wave forms, as influenced by the transmitter parameters and fruit properties, were discussed.

² MATLAB, 1990. The Math Works, Inc., South Natick, MA 01760. USA

Fig. 4.3.7: Directivity diagram of pressure field over the surface of a half-cut melon at 50 kHz excitation frequency, $D = 6$ mm, $r = 25$ mm

Fig. 4.3.8: Calculated and measured pressure field over the surface of a half-cut avocado at longitudinal distance of 3 to 28 mm, 50 kHz excitation frequency, $D = 6$ mm

Fig. 4.3.9: Calculated and measured pressure field over the surface of a half-cut potato at longitudinal distance of 3 to 28 mm, 50 kHz excitation frequency, $D = 6$ mm

Fig. 4.3.10: Calculated 3-D diagram of pressure field over the surface of a half-cut potato at 50 kHz excitation frequency, $D = 6$ mm

The results can be summarized as follows:

1. The classical directivity pattern for a fluid model, being used in metals as well, resembles the experimental results for avocado and potato tissues, despite the fact that asymmetry is evident in the directivity patterns. The same model was not representative of the directivity pattern in melon.
2. A long narrow beam with small side lobes was obtained in the directivity pattern of potato and avocado tissues, suggesting that the frequency range and geometrical size of the transducers used agree with the suggested model.
3. When an energy dissipation term was added to the directional sound pressure model, the model-fitted values of sound velocities and attenuation coefficients for half-cut avocado and potato were lower but still close to those obtained by direct and independent measurements.
4. Further work is needed in order to interpret the half-cut fruit test results in melons

The major part of this chapter was summarized in the paper "Half-cut fruit response to ultrasonic excitation" which have been presented in the 1992 International Summer Meeting of the ASAE in Charlotte, NC.

4.4 A whole Fruit Ultrasonic Testing (Objective 4)

The examination of fruit specimens and half-cut fruit has led to data and results about the ultrasonic response of fruit tissue and its relation to the mechanical properties and quality of the fruit. However, nondestructive testing of fruits, which is the main purpose of the research, implies utilization of these findings throughout a whole fruit testing. The main difficulty in using ultrasonic testing of whole fruit is the extremely high attenuation of the high frequency sonic waves in its tissue. In many kinds of fruits, the attenuation of sound prevents its penetration from one side of the fruit to the other. The non-uniformity of the medium and its complicated constitutive relations add to the difficulty of the NDT. Hence, after examination of various detection methods, two NDT methods have been applied. The first method is based on transmission of the ultrasonic wave throughout the whole fruit, from one side to the other, which is possible in very few products. This method has been applied in Virginia Polytechnic Institute for hollow heart detection in potatoes (Chapter 5 of the report). The second method is based on making local ultrasonic tests over the peel of the fruit, assuming that the internal fruit tissue next to the peel influences the peel response. The investigation in the present chapter will focus on local testing of surface waves which are developed in a whole fruit through ultrasonic excitation. The ultrasonic waves which may be reflected from the internal tissues will not be studied in this stage of the research.

4.4.1 Experimental Setup

The experimental setup for whole-fruit testing includes ultrasonic head with transmitter, receiver and special arrangement to allow inclined transmission and reception of ultrasonic signals. Analysis of the half-cut fruit response to oblique input, as well as for whole fruit testing with inclined probes, showed that the efficiency of lateral wave transmission dose not depend strongly on the angle between the transducers. However, the transmission through the peel strongly depends on the contact pressure of the transducers, and special measures were taken to apply a constant contact force on the fruit by the ultrasonic head.

Two types of ultrasonic heads were designed and built for the whole fruit testing. Head-A includes a special arrangement of inclined transmitter and receiver probes of 50 kHz, to which exponential concentrators were linked (Fig. 4.4.1).

Fig. 4.4.1: Head-A for a whole fruit ultrasonic testing, including two 50 kHz ultrasonic probes, energy concentrators, a gypsum base and electronic scale

The ultrasonic probes of head A were isolated from the other parts of the setup by elastic separators. The probes were inclined towards each other, where the angle between the axes of the transmitter and the receiver was 30° and the distance between their ends over the peel of the fruit was 5 mm. Head-B (Fig. 4.4.2) was more flexible, allowing for motion of the transducers while applying constant force on the fruit peel. The angle between the axes of the transducers of head B was 124° . The system was built in a way that allowed relative motion of the transducers.

Fig. 4.4.2: Head-B for a whole fruit ultrasonic testing, including two 50 kHz ultrasonic inclined movable probes, energy concentrators, a gypsum base and electronic scale

4.4.3 Materials and Method

Velocity of wave propagation in the fruit peel and attenuation of the wave amplitude were examined on melons (*Cucumis melo* L., cv 'Galia'), directly after harvesting for test purposes, and avocado (*Persea Americana* Mill., cv 'Ettinger') which was collected from a packing house.

Melon

Acoustical, mechanical and quality tests were conducted on eleven whole melons which were collected and numbered according to their color from green to yellow. Each fruit was stabilized on a gypsum base and placed on an electronic weight for control of the contact pressure on the fruit. Force calibration tests had shown that the output amplitude of the ultrasonic signal increased linearly with the contact pressure until a force of about 11 N was applied by the ultrasonic head; at this stage, some bruising effects could be seen on the melon peel. For nondestructive testing, the ultrasonic head was laid on the top of the fruit; a constant force of 6.46 N was applied on the fruit by head A, and 4.23 N by head B. The experiment was performed repetitively, using heads A and B. In addition, destructive tests were made by cutting a fresh fruit sample of 20 mm diameter cylindrical core and 10 mm height, in order to define the acoustic parameters by through-transmission. Then, each cylindrical specimen was tested by an Instron Universal Loading Machine for mechanical moduli. About 1 g fruit tissue at the contact point was taken for TSS content examination. An additional slice was squashed over a refractometer (ATAGO PR-1) for an instant definition of Brix percent.

Avocado

Forty avocado fruits of one transport were taken from a packing house, after size classification and for two days in a cooling room at 5°C, for acoustical and mechanical tests. A random selection of five avocados, marked A to E, was done. Four points were marked on the fruit peel at right angles with each other. Those points were defined as A-1 to A-4. These fruits were tested repeatedly, every day, for velocity and attenuation determination of the ultrasound waves, until a full ripening degree was detected after eight days at room temperature. The other 35 fruits were marked randomly from 1 to 35. Each day, five of the numbered fruits were tested first by ultrasonic NDT, and then used for destructive tissue tests. Hence, each day, one group of the numbered fruits was tested for velocity and attenuation determination, and for definition of the mechanical and physiological properties.

Each fruit was placed on a gypsum base for ultrasonic NDT (Fig. 4.4.2). Head B was used in these tests. During the tests, the distance between the transducer ends was increased gradually and the acoustical parameters of the fruit, namely, the flight time and the amplitude of the waves, were measured for velocity and attenuation determination. The NDT of acoustic parameters was done every day on all four points of each of the five alphabetically marked fruits. Subsequently, a group of five numbered fruits were taken for both NDT and destructive test. The penetration test was done

by a Chatillon cone of 6.35 mm, at a rate of 3 mm/sec. Ultrasonic test of tissue specimens was done by cutting a fresh fruit sample of cylindrical core of 20 mm diameter and 10 mm height, to define the acoustic parameters by the through transmission method as described in Chapter 4.2. Each cylindrical specimen was then tested by Instron loading for mechanical moduli determination (Chapter 4.2). For all tests, dry material content of the fruits were examined by the method shown by Degani et al. 1990.

4.4.4 Results and Discussions

Melon

The results of the acoustical, mechanical and physiological properties of a whole melon at 50 kHz are given in Table 4.4.1. The ripeness of the eleven fresh melons was estimated and numbered from 1 to 11 according to their color, as mentioned above, from green to yellow. The acoustical parameters included the transmission time of the ultrasonic wave and the pressure amplitude after crossing the 5 mm distance between the two probes. In this table, E(o) is Young's modulus of a slice close to the peel and E(i) is Young's modulus at an inner layer. The physiological parameters are the Brix percent in the vicinity of the peel [Brix(o)] and at an inner layer [Brix(i)].

Table 4.4.1: Acoustical, mechanical and physiological properties of a whole melon at 50 kHz excitation frequency

Fruit Color Number	Head A		Head B		Young's Modulus		Brix(o) (%)	Brix(i) (%)
	Time (ms)	Amplitude (%)	Time (ms)	Amplitude (%)	E(o) (kPa)	E(i) (kPa)		
1	0.435	135.1	0.438	87.17	54.3	47.5	2.9	5.0
2	0.423	183.2	0.441	84.32	57.0	43.8	3.1	5.5
3	0.638	143.5	0.440	179.35	36.8	25.3	2.6	3.5
4	0.631	199.9	0.439	318.76	57.0	29.2	1.8	3.0
5	0.436	213.1	0.440	336.80	34.5	22.4	3.1	4.9
6	0.633	255.7	0.438	500.00	38.0	25.9	2.9	3.9
7	0.613	125.9	0.446	398.75	38.0	18.7	2.5	3.3
8	0.438	125.2	0.440	400.03	36.8	30.0	2.4	3.4
9	0.629	222.6	0.437	739.48	35.6	23.8	3.1	4.5
10	0.636	97.3	0.437	739.48	38.0	25.9	3.3	5.4
11	0.614	242.2	0.439	589.31	28.5	22.8	2.9	4.5

The control of probe contact-force and the consistency of the readings of Head B were much better than that in the case of Head A; in addition, the pressure amplitude readout of Head B was much stronger than that of head A. When stronger force was applied on head A, the pressure amplitude readout increased, but the inconsistency of the output amplitude was not improved.

The output signal amplitude of the ultrasonic wave through the melon peel is presented in Fig. 4.4.3. It can be observed in the figure that the transferred wave amplitude of head B (124^0 between probes) through the peel increased with increasing color number. Good correlation ($R^2 = 0.844$) was found between the readout of head B and the color number (which was the estimated ripeness of the melons). The strong dependence of wave attenuation on peel color in melons which were picked at the same day can be attributed to the difference in the construction of the peel of green and yellow melons, and the strong effect of the small cracks in the melon peel. The same strong dependence of attenuation on peel color was not observed when head A was applied (30^0 between probes).

Fig. 4.4.3: Transferred amplitude of ultrasonic wave through the melon peel vs. color number, 50 kHz transmission frequency

The flight time of the ultrasonic wave through the melon peel is shown in Fig. 4.4.4. The flight time measured by Head B was practically constant and independent of fruit color number ($R^2 = 0.021$). However, the flight time measured by Head A changed drastically with fruit number, most probably because of errors in determining the position of the leading edge of the output signal [see also Povey (1989)]. Indeed, the flight time readings of head A deviate from each other by finite time steps of 0.18 ms or 0.20 ms (Table 4.4.1), which are 9 or 10 wave fluctuations of the 50 kHz probes. This problem of deviation in signal peak identification did not occur with the clear signal of head B.

When a small groove (1 mm deep) was cut in the melon peel between the two probes, the sound wave of head B practically disappeared, a phenomenon which did not happen when such grooves

where cut in the potato or avocado peel. This phenomenon and the poor correlation between the output signal and the internal fruit properties indicate that the melon peel itself played a major role in the whole fruit wave transfer, with minimum interaction of the internal tissue. Hence, despite the partial success and achievements with whole melons and with melon specimens, it was concluded that the whole melon testing program would be delayed until a stronger ultrasonic system would be available for the research program.

Fig. 4.4.4: Flight time of ultrasonic wave through the melon peel vs. color number, 50 kHz transmission frequency

Avocado - First Group, A to E

The test program of whole avocado fruits was conducted for eight days with the ultrasonic head B and the group of forty fruits as described above. NDT of wave velocity and attenuation in the fruit group A to E were performed every day on each one of the four marked points on each fruit, at distances of 1, 3, 6, 9 and 12 mm between the transducer ends. Figs. 4.4.5 and 4.4.6 show the readout of flight time and pressure amplitude of the ultrasonic wave and their dependence on the distance between the transducer ends. Fig. 4.4.5 illustrates the response of fruit B to the ultrasonic signal at points B1, B2, B3 and B4 on the first day of measurement. Linear regression of the flight time of the signal yielded the velocity of wave propagation in this test. Fig. 4.4.6 illustrates the wave amplitude at the same points on the first day. Exponential regression of the wave amplitude yielded the apparent attenuation coefficient of wave propagation in the test. The correlation coefficients in both cases were quite satisfactory. It is also evident from the figures that both wave velocity and apparent attenuation can be measured nondestructively by the proposed method in the avocado fruit.

Figs. 4.4.5: Flight time of the ultrasonic signal vs. distance between the transducer ends in a whole avocado, fruit B at points B1, B2, B3 and B4 (first day)

Figs. 4.4.6: Apparent attenuation of the ultrasonic signal vs. distance between the transducer ends in a whole avocado, fruit B at points B1, B2, B3 and B4 (first day)

The calculated velocities and apparent attenuation of the ultrasonic signal throughout the first group of five avocado fruits during eight days of storage at room temperature are summarized in Table A-1 of Appendix A. Figures 4.4.7 and 4.4.8 illustrate the change of the velocity and the apparent attenuation with time, respectively. A cubic function of time was selected for the velocity and a parabolic function for the apparent attenuation, in order to represent the experimental data. The scattering of the local-point measurements is obvious. This problem can be reduced by repeating measurements and averaging data points of the same fruit. However, the general tendency of the data points is clear: moderate fluctuations of the wave velocity and increased attenuation of the whole avocado with time.

Wave velocity and attenuation versus time, for a whole avocado and for an avocado tissue specimen of all 40 fruits during eight days, are shown in Figs. 4.4.9 and 4.4.10, respectively. The dependence of the whole fruit parameters of the 40 avocados on time is about the same as that of the first group alone (Fig. 4.4.6 and 4.4.6). The respective values of velocity in the internal tissue, as measured by the destructive tests of 35 fruits, are slightly lower than the whole fruit values; however, both curves have similar type of time dependence (Fig 4.4.9). The parabolic curve fitting of the internal attenuation versus time was less successful (Fig 4.4.10).

E-Modulus (E) and the firmness (F) of the fruit versus time, as measured by the destructive tests during eight days, are presented in Figs. 4.4.11 and 4.4.12, respectively. Both E and F reduced with time, but not in a regular manner (the linear curve fitting of these figures is for indicative purposes only). Small changes could be observed in the stiffness parameters of the fruits during the first days of storage (Figs. 4.4.8 and 4.4.9). Then, within about 24 hours, both E and F reduced sharply and the fruits became much softer. This sharp change in the stiffness of the individual fruit did not happen at the same time for the different fruits, as shown in the figures. When the change of fruit stiffness had happened, the low values of E and F did not change much with time. As expected, high correlation was found between the measured E-Modulus and fruit firmness (Fig 4.4.10).

The relation between E-Modulus and whole fruit velocity (Fig. 4.4.11) is similar to that with time (Fig. 4.4.8). The relation between the two variables is non-linear; the linear curve fitting was added to the data for indicative purposes only. The high E values of stiff avocado are indicated by low velocities of wave propagation through the peel of the whole fruit, while high wave velocities indicate low E values (soft fruit). The same phenomenon was observed when fruit firmness was correlated with wave velocity. Since both E and F tests in avocado indicate its stiffness or ripeness degree, it may be possible to evaluate the ripeness degree of avocado through the nondestructive velocity test. Ultrasonic attenuation test may be employed for this purpose as well.

A problem associated with the interpretation of the ultrasonic measurements is the scattering of the experimental data; this problem is expected in local testing of a biological material. More reliable whole fruit properties may be obtained by averaging several data points of local tests over the same fruit.

Figs. 4.4.7: Velocity of the ultrasonic wave vs. time, NDT of a whole avocado during eight days, first group of fruits

Figs. 4.4.8: Apparent attenuation of the ultrasonic wave vs. time, NDT of a whole avocado during eight days, first group of fruits

Figs. 4.4.9: Wave velocity of a whole avocado (DW) and avocado tissue (V_t) vs. time during eight days, first and second group of fruits

Figs. 4.4.10: Apparent attenuation of a whole avocado (A_w) and avocado tissue (A_t) vs. time during eight days, first and second group of fruits

Figs. 4.4.11: E-Modulus of avocado tissue vs. time during eight days, second group of fruits

Figs. 4.4.12: Firmness of avocado tissue vs. time during eight days, second group of fruits

Figs. 4.4.13: E-Modulus of avocado tissue vs. fruit firmness during eight days, second group of fruits

Figs. 4.4.14: E-Modulus of avocado tissue vs. wave velocity of a whole fruit during eight days, second group of fruits

4.4.5 Summary and Conclusions

Nondestructive testing of whole melon and avocado fruits was performed using two experimental 50 kHz ultrasonic heads. Special design of the selected head allowed to apply constant contact force on the fruit peel by the ultrasonic probes. Analysis of the results led to the following conclusions:

1. The pressure amplitude of the ultrasonic signal strongly depended on the loading force of the transducers on the fruits.
2. A 124° Inclination angle between the transducers and uniform load application improved the performances of the ultrasonic head in whole fruit testing.
3. The attenuation of the ultrasonic wave of the whole melon correlated well with its color and the estimated ripeness. However, very poor correlation was found between the melon peel signal and its internal properties.
4. The transmission time in avocado was measurable and has a clear linear dependence on the distance between the ultrasonic probes. As expected, the amplitude of the pressure waves decreased exponentially with increasing distance between the ultrasonic probes.
5. Puncture force (firmness) and Young's modulus of the avocado tissue correlated well with each other and strongly decreased with the storage time and softening of the fruit.
6. Changes in sound velocity and attenuation coefficient of the ultrasonic wave during the softening process of the avocado fruit may be used for maturity and shelf-life determination of avocado fruit.
7. A stronger ultrasonic source is needed in order to penetrate the melon peel for internal properties determination. Further study is needed for the verification of the present findings and their application in a commercial nondestructive testing system.

5. VIRGINIA POLYTECHNIC INSTITUTE REPORT

5.1 Hollow Hearts in Potatoes

Hollow heart in potatoes is a physiological disorder characterized by an irregularly shaped cavity in the pith region of the tuber with a normal external appearance. Development of the disorder is often associated with rapid growth that may be preceded by a period of moisture or nutritional stress. Several techniques have been developed for non-destructive detection and separation of potato tubers with hollow heart. These include use of tuber size or specific gravity, x-rays, light transmittance and ultrasound.

Finney and Norris (1978) attempted to cut down the incidence of hollow heart potatoes by separating the tubers on the basis of individual tuber weight or specific gravity. They reported that the incidence of hollow heart for a sample of 106 potatoes was 0.0% by weight for tubers weighing less than 200 gm, while for tubers 600 gm and greater in weight it was 100.0%. The same sample of tubers was separated based on specific gravity. Tubers with specific gravity of 1.050 or less had an incidence of hollow heart of 66.6% by weight, whereas tubers with a specific gravity of 1.071 to 1.080, and 1.081 and greater, had 9.2% and 4.2% hollow heart, respectively. However, there was no well-defined value of specific gravity at which hollow hearts began or cease to exist, although there were more hollow heart potatoes in lower specific gravity classes. The reason for this poor definition is that there is considerable variation in the specific gravity of various parts of the potatoes. When the incidence of hollow heart is high, a larger proportion of the crop would have to be discarded to meet grade standards for hollow heart. Moreover, the practical difficulties of making specific gravity measurements would also make the method impractical. Therefore, this is not an economically effective mean of removing hollow heart potatoes from a field lot of potatoes.

Hollow hearts of potatoes, which are not visible externally, can be detected clearly in an x-ray picture. Finney and Norris (1978) suggested an x-ray scanning technique for automatic sorting of hollow heart potatoes. The scanning x-ray technique was used to detect tubers with hollow heart and from the experiment results they attempted to determine some objective criterion by which automatic sorting of defective potatoes could be obtained. A potato was placed in an x-ray field and a scanning detector traversed the length of the potato. The output of the detector was amplified, digitized and fed to a digital computer for analysis and recording. All 14 tubers with hollow heart in a sample of 106 tubers were detected using this method. Better results were obtained using tubers in air than using tubers submerged in water. There have been some commercial x-ray machines in use for detection of hollow heart in potatoes. The potential danger and the cost of operating of x-ray equipment have hindered the development of this technique into a fully automatic system for the hollow heart problem.

Light transmission has been used in non-destructive testing of hollow hearts in potatoes by isolating narrow beams of light of a specific wavelength and measuring which is transmitted, reflected, or absorbed by the samples. In potatoes, it has been observed that normal optical properties are modified in consistent ways in the presence of certain disease and defects. Birth

(1960) described a procedure for detection of internal defects of potatoes using a spectrophotometer to measure the spectral absorption curve of whole tubers. The image of a hollow heart cannot be seen when visible or near infrared energy was used, but there was a selective absorption of energy in the near infrared region which was indicative of the hollow heart. This selective absorption of energy was due to the discoloration in the vicinity of the hollow heart. The potato with hollow heart absorbed considerable more energy in the 650 to 750 μm region than the sound potato. No large differences were observed between sound and hollow heart tubers at 800 μm . By using the differences in optical density (O.D.) between 710 and 800 μm to separate tubers, he was able to remove 98% of tubers with hollow heart in a sample of Irish Cobbler potatoes. In a test with Katahdin potatoes, 81% of all discolored tubers were deleted including potatoes with decay, greening, blackspot and hollow heart. The method did, however, result in the incorrect diagnosis of a small percentage of tubers free of disorders. The rejection rate for potatoes with greening or decay was low because greening and decayed areas occurred at random locations on the tuber and the apparatus was designed to look at a cylinder of tissue through the center of the potato. Variation in O.D. resulted from variation in the size and shape of individual tubers. Difficulties in measurement also resulted from variation in spectral absorption due to varying skin thickness or skin thickness relative to tuber thickness, the presence of scarred tissue and soil on the tubers. Yellowing of flesh in Irish Cobbler potatoes from long term storage did not affect detection of tubers with hollow heart.

As mentioned, Watts and Russell (1985) have attempted initial study on use of ultrasonics for detection of hollow heart in potatoes. They pointed out that there were several challenges to overcome before ultrasonics could be used commercially. The attenuation coefficient of potato tissue was quite high (1.0 dB/mm), and the ultrasonic velocity in potatoes was about two-thirds of that in water (900 m/s). They suggested that the high attenuation coefficient was due to the scattering of the sound both by the cellular structure of the potato and the presence of 1 to 2% air in the potato tissue. The major problem was the high attenuation characteristics of potato tissue, especially at high frequencies. At low frequencies, the resolution decreased and a large transducer was required. The resolution at 175 kHz was thought to be barely sufficient to obtain a good indication of hollow hearts in potatoes. Therefore, the optimum frequency to obtain reproducible results with maximum resolution must be sought and ultrasonic detection of hollow heart has potential if the attendant problems could be overcome.

5.2 Instrumentation and Experiment Methods - V.P.I.

Experiments were carried out at an early stage of this study using the Ultrasonic C-scanning system without much success. The system included a Panametrics ultrasonic pulser/receiver 5055PR, a Sonotek MC-33 3-Axes stepper motor and driver pack, a Sonotek STR*8100 a/d board and the C-scanning program. The sample tissues cut from potatoes and apples of 5 to 20 mm thickness were used for these tests using immersion technique with water as couplant. High

reflection and attenuation of incident sound waves were observed because of the poor transmission when using both 500 kHz and 1 MHz transducers. Results obtained from the C-scan were insignificant because the image obtained was that of the reflected sound and this was especially true with apple samples. The reason for the poor penetration was due to insufficient power level of the instrumentation and the type of transducers used. Another important disadvantage of the system was that it could not be used to test a whole fruit or vegetable, which was one of the primary plans of this study.

5.2.1 Ultrasonic Nondestructive Testing System

Based on the early experiments, another ultrasonic non-destructive evaluation system was developed at Department of Agricultural Engineering, Virginia Tech for determination of basic acoustic properties of fruits and vegetables; namely, velocity of wave propagation by through-transmission and pulse-echo methods, wave attenuation, reflection and transmission spectrum analysis. A schematic diagram of the test instrumentation for ultrasonic measurements including a system for frequency domain analysis is illustrated in Fig. 5.2.1. The basic setup included an Ultran BP 9400A high-power burst pulser, an Ultran BR 640A broadband receiver, a Tektronix 2232 digital storage oscilloscope, and a pair of transducers. The driving voltage from the pulser for transducers is 400 volts out of 4. The pulse width and separation time between pulses can be adjusted for transducers of different frequencies.

Fig. 5.2.1: A schematic diagram of the test instrumentation for ultrasonic measurements

Here a pulsar sends electrical energy bursts into one of the transducers, causing the transducer to oscillate and launch a broadband ultrasonic pulse in the test sample. The ultrasound travels through the material until it encounters a boundary or discontinuity in the material. In such cases, a portion of ultrasonic energy will be reflected. The transmitted ultrasound is received by another transducer and amplified and displayed on the oscilloscope screen as real time rf traces.

A microcomputer-controlled serial interface allowed the capture of the digital signal from the oscilloscope via a GPIB interface of the computer for further analysis. The testing system also included a signal analysis software, ACQUIRE, which had a function to compute frequency spectrum of the ultrasonic wave by means of the Fast Fourier Transform (FFT). Included were two pairs of dry-coupling broadband transducers with frequencies of 250 kHz and 1 MHz, respectively. The diameters of the transducers were 6.36 mm (0.25 inch). These dry-coupling transducers could be placed directly on the test material surface for efficient ultrasound propagation through the material because a solid, compliant transitional layer (matching/protective layer) that was acoustically transparent was incorporated on the surface of the active piezoelectric element. This matching/protective layer of soft material subject to pressure could adapt itself to the peak and troughs of the surface of the object, making good contact over a large part of the area. Such a soft material may, in effect, be regarded as a substitute for liquid couplant. Dry-coupling transducers are more suitable for characterizing porous and liquid-sensitive materials. Fruit and vegetable tissues are usually porous and air-containing. As discussed in the literature review previously, when a liquid was used as a couplant, the attenuation coefficient of fruit and vegetable tissues decreased with time due to the entrance of the liquid into the intercellular voids of the tissues. However, there are limitations to the dry-coupling transducers. The dry-coupling transducers could not be lid over the surface of a test material. They also cannot be used efficiently if the surface of the material is too rough.

Since the dry-coupling transducers were used, it was very important to ensure constant pressure between the transducers and the test sample. A special holding device was designed and built for the transducers and samples. This device held a pair of transducers in line on opposite sides of the test sample, while allowing their separation to be adjusted to accommodate various sample sizes. Pressure applied on the sample could be adjusted to the desired level and held constant by a cylindrical compression spring arrangement mounted behind the transducers. The same amount of pressure could be applied to each sample by means of the pressure-indicating pointer mounted on the sample holder.

Based on the literature search for this study, no one has successfully transmit the ultrasonic waves through a whole fruit or vegetable, such as a whole potato. The results reported so far are limited to the sample slices of fruits/vegetables due to the insufficient power of instrumentation. However, with the experimental system described above, the ultrasound can successfully transmit through some whole products, such as a whole potato tuber, at the frequency up to 1.0 MHz.

5.2.2 Experiment Procedures

Throughout this study, all the measurements were made by using dry-coupling direct-transmission method. Ultrasonic NDT was performed by studying the time and frequency domains corresponding to the ultrasound transmitted through a test sample - a whole product or a specimen cut from the tissue of a product. In time-domain ultrasonics, the signal was typically represented on an oscilloscope as real time rf traces. The horizontal and vertical axes of such traces represented time and amplitude of the transmitted or reflected signals. Material characterization information that could be obtained by time-domain ultrasonics included the velocity of waves, elastic properties, identification and location of defects, dimensional analysis, etc. However, only time-domain analysis was inadequate for signals that exhibit complex frequency spectra. Conversion of the time-domain ultrasonic signals into its frequency domain coordinates by means of FFT generates the frequency domain signals. Frequency domain ultrasonics also provided means for attenuation analysis of the testing material.

In addition to the ultrasonic measurement, an Instron Universal Testing Machine was used to determine the modulus of elasticity of the acoustically tested fruits and vegetables, which is an important texture attribute in connection with the quality evaluation in fruits and vegetables.

Determination of ultrasonic velocities

Ultrasonic velocities were determined by using cylindrical specimen removed from a product along different orientations (longitudinal, radial, or cross-sectional), depending upon the type of the product. The sample was placed between the two transducers and aligned along the center line of the sample and the transducers. Pulsed ultrasound was used to measure time-of-flight (TOF) by the dry-coupling direct-transmission method. Measurements of TOF corresponding to the known distance traveled by ultrasound was made from the Tektronix 2232, a 100 MHz digital storage oscilloscope. The mechanisms of the TOF measurement included the establishment of a reference signal corresponding to the "zero" position on the oscilloscope. In order to establish the "zero" reference point, the TOF corresponding to the transducer match/protective layers has to be considered, or an error would be introduced into test sample TOF. The two transducers - transmitter and receiver - were placed together with their active regions touching each other. The transmitted signal in this case corresponded to the TOF through the matching/protective layers of the transducers. A cursor was placed at the leading edge of this signal to indicate the zero or the reference point from where TOF corresponding travel distances of test samples were measured. The other cursor was placed at the leading edge of the transmitted signal through a test sample and the TOF for the test sample was displayed on the screen of the oscilloscope.

Cylindrical sections of tissues of 20.6 mm diameter were removed from the testing fruits/vegetables with a sharp cork borer and trimmed to an initial length of 20-25 mm, depending upon the type of the product. These specimens were placed between the transducers coaxially. The sample holder described previously was used to hold the specimens between the transducers under the same pressure each time. Samples were serially shortened and the TOF for each sample was

measured using the method described above. A simple linear regression method was used to determine ultrasonic velocity using time-of-flight information versus varying sample thickness. The dependent variable was the time while the sample thickness was the independent variable. The inverse of the slope of the regression line was the average velocity of the product under investigation.

Determination of attenuation coefficient

Pulse-echo method is widely used for ultrasonic measurement of attenuation properties of a material. But this method could not be used for high attenuative materials such as fruit and vegetable tissue since it is very difficult to obtain multiple echoes in these materials. Therefore through-transmission method was used. Measurements of attenuation coefficients as a function of frequency were made in connection with velocity measurements for a testing product. To determine the attenuation coefficient for a product by using through-transmission method, the cylindrical specimens were shortened serially to different thicknesses. The time domain signals obtained for velocity measurements were now captured by the microcomputer through the GPIB interface. The transmitted ultrasonic waves were window at same size converted into their respective frequency components by a spectrum analysis using Fast Fourier Transformation techniques (FFT). Two frequency domain spectra obtained from a sample at two different thickness were then compared and the attenuation coefficient at a certain frequency was calculated according to Eq. (3.2.18). After finishing calculation of attenuation coefficient at different frequencies, Eq. (3.2.9) was fitted and α_0 and n were calculated for the product.

In some cases, attenuation coefficient was given in terms of nominal frequencies of transducers. However, if the transducers are broadband, the ultrasonic energy is spread over a frequency spectrum in pulse excitation. Since attenuation coefficient α changes with frequencies, simple comparisons of the amplitudes of transmitted ultrasonic signals at different thicknesses may be more precisely termed as 'apparent attenuation coefficient' of the wave. The advantages of using apparent attenuation coefficient includes: (1) the calculation is much simpler than frequency dependent attenuation; (2) it can provide useful information of the attenuation properties of materials under test for comparison purpose on the relative basis.

The key to the success of attenuation measurement using through-transmission method was to apply constant pressure on transducers when measurements were made for each specimen. Therefore the sample holding device was adjusted carefully so that the transducers applied a constant pressure on the test specimens for each measurement.

Detection of hollow hearts in whole potatoes

In the preliminary study of acoustic behavior of a good potato and one with hollow heart, a simulated hollow heart in a potato was made in the laboratory. After recording the transmitted wave from a good potato tuber, a cylindrical cork was removed for the flesh of the same potato up to its center by using a cylindrical cork cutter. Small hole gages were used to make a hollow heart in the

center of the potato. The mashed part of flesh in the center of the potato was sucked out by a vacuum pump. The cylindrical cork was then put back into the cylindrical hole. This potato with simulated hollow heart was tested again in such a manner that the ultrasound would transmit through the hollow heart and the transmitted waves were recorded. Frequency analysis for the transmitted signals was carried out by using FFT technique. The results of the preliminary study indicated that ultrasonic waves could be used to detect hollow hearts in potatoes, and the experiment was carried on to the potatoes with real hollow hearts.

Potatoes used in this study for hollow-heart detection were Atlantic potatoes provided by Midwest Potato Research Laboratory at Minnesota. The incidence of hollow hearts in these potatoes was more than 50%. The potatoes were placed in cold storage room of 1 to 2°C until experiment time. They were removed from the storage room at least 24 hours prior to any tests to allow them reach room temperature. The potatoes were then numbered randomly, weighted to nearest gram, and their volumes and dimensions were also measured. The potatoes were then tested using ultrasonic waves by dry-coupling direct-transmission method at 250 kHz. The potatoes were oriented so that the ultrasound passed through the shortest dimension of the potatoes.

The transmitted ultrasonic signal through a whole potato under test was displayed on the digital oscilloscope, the digital data was then acquired by means of the microcomputer-controlled serial interface GPIB and saved on disks for later analysis. Power density spectrum for each tested potato was calculated by using Fast Fourier Transform technique. The windows used for carrying out the FFT were started from the leading edge of transmitted signals with duration of 250 μ s. The measurements were quantified by using the frequency analysis of the transmitted ultrasonic signals and by applying a signal analysis method based on power spectral moments. The 0th spectral moment is defined as following:

$$M_0 = \int_{-\infty}^{+\infty} S(f)df \quad (5.2.1)$$

where $S(f)$ is power spectral density, f is frequency. Therefore, M_0 is the area under the power spectrum of the transmitted ultrasonic signals. M_0 was calculated for each tested potato by using numerical integration method.

After finishing the nondestructive evaluation, the potato was cut into two halves to observe the internal conditions. If there was a hollow heart in the tested potato, the volume of the cavity was determined by using a Pyrex burette and recorded together with the dimensions of the cavity. Then cylindrical samples were taken from the healthy tissue of the potato to determine its ultrasonic velocities and modulus of elasticity.

Detection of Modulus of Elasticity

Modulus of elasticity has been used to measure fruit and vegetable firmness, which is an important texture attribute in fruits and vegetables in connection with the quality evaluation during

storage for fresh market as well as prior to processing. Modulus of elasticity was measured by conventional uniaxial compression tests using cylindrical specimen after the acoustic measurements.

Following the tests for acoustic measurements, a cylindrical specimen of 20.6 mm diameter was removed from the flesh of the same fruit/vegetable by using a small cork-boring machine and a cylindrical cutting tool. This cylindrical specimen was then cut into a predetermined length, the size of which was dependent upon the type of the product, and weighted. The dimensions of the specimen (length and diameter) were measured with a high-accurate micrometer. Modulus of elasticity was determined for each specimen after the acoustic measurements by conventional objective methods, and an Instron universal testing machine was used for the uniaxial compression tests. The machine for these tests was calibrated to provide a rate of deformation of 20 mm/min with a 200-lb load cell. The cylindrical specimen was loaded between the parallel compression plates. The force-deformation curves were plotted directly on the recorder of the machine, and at the same time the digital data was acquired and stored on disks by a microcomputer for later analysis.

Biological materials such as fruits and vegetables usually falls short of meeting the criteria of an elastic material. In these materials, even at small strains, there is always some residual deformation remaining after first loading and unloading cycle. Therefore, modulus of deformability or apparent elastic modulus (representative of the Young' modulus for viscoelastic materials) was used to approximate the initial linear portion (slope) of the stress-strain curves obtained with the Instron universal testing machine without accounting for the changes in the ratio of stress to strain during the unloading process. In this report, the apparent modulus will be used to approximate the modulus of elasticity of tested fruits or vegetables and the words "modulus of elasticity" and "apparent modulus" will be used interchangeably.

Determination of property changes of potatoes during storage

Any mechanical property evaluated for an agricultural product is associated with a particular stage of the living process (e.g., maturity level) of the material. Therefore, the properties must be evaluated for the same product at various maturity stages and storage conditions in order to specify its mechanical behavior.

Potatoe's physical and acoustic property changes during the storage period were evaluated in this study. The potatoes used were 'Yukon-Gold' potatoes provided by local farmers in Virginia. The potatoes were harvested on September 13, 1991, and left at room temperature for curing until October 3, 1991, after which they were removed to a 1 to 2⁰C storage room. At least 24 hours prior to any tests, the potatoes were removed from the cold storage room and placed at room temperature. The experiment was conducted using cylindrical specimens cut from the potato tissues at 250 kHz and 1 MHz and by dry-coupling trough-transmission method. Six test groups were carried out on a regular basis - once every four weeks with ten potatoes tested each time. The first experiment was conducted right before the potatoes were put into the storage room. Ultrasonic velocities and attenuation coefficients were determined each time along two orientations - longitudinal and transverse - using the methods described above. Modulus of elasticity was also determined each time

for the same group of potatoes by using the Instron universal testing machine.

5.3 Results and Discussion

5.3.1 Verification of Basic Laws and Principles (Objective 1)

The theoretical study and verification of basic laws of wave propagation were given previously in this report. Preliminary experiments were conducted with test samples and whole products. This early phase of study involved selection and re-evaluation of acoustic excitation and detection devices, coupling methods, proper frequency range and signal analysis methods for detection of internal properties of agricultural products. The preliminary results of experimental work led to development of the ultrasonic nondestructive evaluation system and signal analysis system described earlier in this report, and the systems were used in later experimental work and studies of quality of selected fruits and vegetables.

5.3.2 Screening of Potential Fruits and Vegetables (Objective 2)

A wide variety of fruits and vegetables was tested to investigate their potential for quality evaluation using ultrasound. Among the tested fruits and vegetables, the ultrasonic waves could not be transmitted through some products, such as a whole melon, cucumber, banana, apple, tomato, avocado, pear, and peach due to high attenuation properties of the tissues of these fruits and vegetables. However, the sound waves could be transmitted through the sliced sample tissues of these fruits and vegetables up to 20 mm thickness so that the ultrasonic velocities could be determined for these fruits and vegetables. For a whole kiwi fruit, the transmitted ultrasonic signal was too weak to allow meaningful interpretation; also, the pressure applied to the fruit in holding the transducers in contact with the fruit tended to bruise it. Ultrasonic waves were successfully transmitted through a whole potato tuber at frequencies up to 1 MHz. Potato tubers were used as a product for detailed acoustical studies for quality evaluation using ultrasound. Although the ultrasonic waves could not transmit through a whole apple, cylindrical apple tissues were used to investigate their acoustic properties.

5.3.3 Systematic Study of Relations Between Quality of Products and Their Acoustic Response (Objective 3)

Ultrasonic propagation parameters, such as velocity and attenuation, are dependent on the physical properties of the material through which the sound is traveling. Therefore, investigation of these parameters could provide important information about material properties. Modulus of elasticity was also determined for the tested fruits and vegetables as an important texture attribute in connection with the quality evaluation. Two varieties of potatoes were investigated in this study, Yukon-Gold and Atlantic. Yukon-Gold potatoes were provided by local farmers at Virginia and they were used to investigate the physical and acoustical property changes during the storage for six

months. No hollow hearts were found in Yukon-Gold potatoes. Atlantic potatoes were provided by Midwest Potato Research Laboratory and more than 50% of the potatoes had hollow hearts. Three varieties of apples were also tested for changes of acoustic properties with the texture changes.

Physiological changes of potatoes during storage

The investigation of Yukon-Gold potatoes concentrated on the physical and acoustical property changes during the storage period. Ultrasonic velocities, attenuation coefficients and modulus of elasticity were determined each time along two orientations - longitudinal and transverse - using cylindrical specimen cut from the potato tissue. The sample length for determining ultrasonic velocity and attenuation coefficient was 24, 27, 10 mm. The sample length used for determining modulus of elasticity was 20 mm.

It was found that there was no significant difference between the ultrasonic parameters measured at frequencies of 250 kHz and 1 MHz. This may be due to the fact that these transducers are broadband transducers. Figs. 5.3.1 and 5.3.2 are the plots of mean values for ultrasonic velocity and modulus of elasticity, respectively, for 10 specimens in each test. It can be seen that ultrasonic velocities and elastic moduli increased with storage time, and started falling when the experiment was close to the end. Although the average values of longitudinal velocity were higher than that of transverse velocity, no significant differences were found between them statistically. However, the differences between elastic modulus alone for the two orientations were found statistically significant.

Figure 5.3.3 is a typical graph of frequency dependent attenuation coefficient of 'Yukon-Gold' potatoes. It can be seen that as frequency increased, attenuation coefficient was also increased. However, calculation of frequency dependent attenuation is much more complicated and time-consuming than that of apparent attenuation coefficient. Since we are more interested in the changes of attenuation properties during the storage period and comparison of the changes on the relative basis, the apparent attenuation coefficients were calculated for each tested potato. The results for all the tested potatoes are listed in Appendix B. Figure 5.3.4 is the plot of mean values of apparent attenuation coefficients measured for 10 samples in each test. As shown in Fig. 5.3.3, the apparent attenuation coefficients decreased during the storage period until 1.14.92, when the apparent attenuation coefficients had higher values than that of the previous test, and then decreased again on the next or last tests.

Detection of hollow hearts in Atlantic potatoes

The hollow hearts in Atlantic potatoes were successfully detected nondestructively by using the dry-coupling direct-transmission method at 250 kHz. The transmitted ultrasonic signal through a whole potato under test was first recorded in time domain along with the system setup. Figs. 5.3.5 and 5.3.6 are plots of a typical good potato and one with hollow heart, respectively. However, the time-domain ultrasonic signals were not enough to provide information about hollow heart. The Fast Fourier Transform technique was used for the frequency component analysis of the transmitted

Fig. 5.3.1: Changes of ultrasonic velocity with time in Yukon-Gold potatoes

Fig. 5.3.2: Changes of elastic modulus with time in Yukon-Gold potatoes

Fig. 5.3.3: Frequency dependent attenuation coefficient of 'Yukon-Gold' potatoes

Fig. 5.3.4: Changes of apparent attenuation coefficients during storage of Yukon-Gold potatoes

Fig. 5.3.5: Atlantic potato #10, weight 309 g, cavity size = 0

Fig. 5.3.6: Atlantic potato #5, weight 424 g, cavity size = 48 mm

signals. Figure 5.3.7 is a plot of the frequency spectra of the time-domain signals presented in Figs. 5.3.5 and 5.3.6. The signal amplitude of transmitted ultrasonic frequency components through the hollow heart potato was much less than that of solid ones due to the reflection and interference of sound waves within the potato.

In order to quantify the ultrasonic measurements for the test potatoes, the energy content distributed over the frequency bandwidth, generally referred to as power density spectrum of the signal, was obtained using FFT method. Figure 5.3.8 is a plot of power density spectra of signals for the same potatoes as in Fig. 5.3.7. The spectral moment M_0 , which was the area under the power spectral density curve as shown in Fig. 5.3.6, was calculated by using numerical integration method and used as the quantified measurement for each potato tested. The calculated M_0 's are listed in Table 5.3.1. Table 5.3.1 also gives other physical and acoustical information of 41 tested potatoes, which include ultrasonic velocity, modulus of elasticity, potato volume, density of whole potato, wave path length and cavity size of hollow heart potatoes.

Figures 5.3.9 and 5.3.10 give the plots of M_0 vs. volume of potatoes and wave path length of tested potatoes, respectively. Potatoes with hollow heart transmitted much less ultrasonic energy than that of good potatoes. Under the instrument setting conditions of the experiment for detecting hollow hearts in Atlantic potatoes, as shown in Figs. 5.3.9 and 5.3.10, when $M_0 > 0.2$ for a tested potato, there was no hollow heart found in the potato by cutting it into two halves. On the other hand, when $M_0 < 0.2$, hollow hearts were found in the tested potatoes. Among 41 Atlantic potatoes tested, all 26 hollow-heart potatoes were identified without any failure. Therefore, the parameter could provide a way of analyzing the ultrasonic measurements for quantitative nondestructive evaluation of hollow hearts in potatoes.

Since the wave path length was longer for bigger potatoes and more attenuation was involved in wave propagation, it was expected that M_0 values for bigger potatoes would be lower than that for smaller potatoes, since less ultrasonic energy could pass through the bigger potatoes. However, experimental results indicated that there was no relation between the path length or size of potatoes and M_0 , as shown in Figs. 5.3.9 and 5.3.10. The reason for this may be that the coupling conditions of the transducers to a whole potato were inconsistent due to the nonuniform shapes of the potatoes. When the transducers were not in perfect contact with the surface of a potato, less ultrasonic energy would be transmitted into the potato, no matter what size the potato was. This problem may be solved by using some coupling materials, such as coupling gels, on the surface of potatoes instead of using dry-coupling method.

Fig. 5.3.7: Frequency spectra of Atlantic potato #5 and # 10

Fig. 5.3.8 : Power density spectra of Atlantic potato #5 and # 10

Fig. 5.3.9: Spectral moment of Atlantic potatoes vs potato volume

Fig. 5.3.10: Spectral moment vs path length of potato

Table 5.3.1: Summary of experimental data of Atlantic Potatoe

Potato	Elastic modulus (MPa)		Velocity (m/s)		Potato volume	Cavity volume	Density	Path length	Mo
Number	E_t	E_l	V_t	V_l	cm ³	cm ³	gm/cm ³	mm	v ² /s
1	3.24	3.55	645.83	651.77	585	3.4	1.101	78.0	0.0154
2	3.28	3.54	635.05	649.11	262	0.0	1.111	61.1	0.5570
3	3.08	3.30	559.14	626.71	563	3.5	1.103	74.1	0.0324
4	3.81	3.74	620.23	694.23	458	4.1	1.103	74.5	0.0216
5	3.91	4.23	763.33	721.49	386	4.8	1.098	69.5	0.0971
6	2.90	3.22	577.49	626.28	342	0.0	1.105	65.7	0.4380
7	2.82	3.46	486.87	506.60	337	0.6	1.080	69.0	0.0216
8	2.78	3.44	657.90	643.69	725	5.7	1.094	85.4	0.0073
9	3.01	3.29	684.78	682.39	402	0.0	1.112	76.8	0.3450
10	3.13	3.00	518.77	613.05	282	0.0	1.096	64.7	0.5230
11	3.25	3.46	637.37	611.64	393	0.0	1.109	71.3	0.5110
12	3.51	3.90	673.03	712.03	399	8.4	1.088	66.0	0.0820
13	3.07	3.75	639.01	643.87	482	0.0	1.108	76.5	0.2770
14	4.18	4.84	745.18	819.45	513	20.1	1.058	72.7	0.0684
15	4.22	4.32	729.40	764.85	480	7.8	1.083	69.8	0.1060
16	3.44	3.67	554.51	561.65	550	0.0	1.085	77.0	0.7210
17	3.56	3.58	605.68	684.72	639	3.8	1.097	82.1	0.0304
18	3.48	3.87	548.52	680.15	453	4.0	1.086	73.0	0.0526
19	3.54	3.71	589.69	658.38	469	0.0	1.102	76.0	0.7660
20	3.54	3.78	723.95	758.48	368	6.3	1.092	72.6	0.0799
21	3.36	3.77	661.02	643.82	352	0.0	1.105	69.3	0.7050
22	3.72	4.07	798.85	800.32	351	0.0	1.108	71.5	1.0300
23	3.92	4.08	573.28	632.18	388	8.6	1.072	66.2	0.0330
24	3.43	4.11	679.36	704.03	325	3.7	1.098	72.1	0.1720
25	3.73	4.21	735.98	670.75	435	1.3	1.099	76.2	0.0903
26	3.08	3.65	706.11	726.94	392	1.8	1.105	70.1	0.0500
27	3.40	3.69	747.87	714.83	642	0.0	1.097	89.7	0.6590
28	4.78	5.02	688.57	804.36	496	15.8	1.056	74.4	0.0555
29	4.29	2.35	740.24	772.72	414	0.0	1.109	76.2	0.8620
30	3.45	4.08	660.75	698.54	543	1.8	1.088	71.0	0.0515
31	4.13	4.25	763.94	701.61	333	1.7	1.099	69.9	0.1980
32	3.80	3.71	595.82	636.60	276	5.4	1.080	64.2	0.0790
33	3.56	3.74	744.77	685.83	345	4.7	1.090	68.7	0.1090
34	4.33	4.17	755.24	710.86	684	0.0	1.098	85.4	1.0260
35	4.22	4.56	738.73	735.80	347	3.8	1.104	57.2	0.1610
36	3.50	3.39	582.23	596.72	590	0.0	1.092	79.1	0.2890
37	3.44	3.81	651.02	676.38	573	8.5	1.082	77.2	0.0106
38	3.54	3.68	628.90	694.07	352	4.8	1.091	65.2	0.0494
39	3.47	3.90	578.50	654.29	453	0.0	1.104	74.3	0.4620
40	3.66	3.78	761.23	757.30	411	8.7	1.080	71.4	0.0827
41	3.51	4.21	686.42	714.03	352	2.1	1.108	66.8	0.0599
Avg	3.56	3.80	660.35	683.96	442.49	---	1.0946	72.49	---
Var	0.20	0.23	6036.06	4172.24	13263.46	---	0.0002	42.61	---

E_t = modulus of elasticity measured transversely

E_l = modulus of elasticity measured longitudinally

V_t = velocity measured transversely; V_l = velocity measured longitudinally

Figure 5.3.11 is a plot of measured density for a whole potato and the observed cavity volume in it. It can be seen that fairly good correlation existed between the density and cavity size of the potatoes ($R^2=0.658$). When the volume of a hollow heart in a potato increased, the measured density was decreased. However, due to the large variations of the data, it would be difficult to establish criteria for detection of hollow hearts in potatoes based on the density measurements. The accuracy would be too low to permit its use as a grading technique.

From the frequency spectra for the tested Atlantic potatoes, it can be found that the frequencies which could be transmitted through a whole potato were no higher than 150 kHz, the higher frequency components were attenuated and filtered out as they were passing through the potato. Therefore, the frequencies that can be efficiently used to detect hollow hearts in potatoes should be in the range of 50 kHz to 150 kHz. Frequencies lower than 50 kHz would probably not give enough resolution for detection of hollow hearts in potatoes.

Fig. 5.3.11: Potato density vs cavity volume

Acoustic properties of apple tissues

Although the ultrasonic waves could not be transmitted through a whole apple, cylindrical apple tissues were used to investigate its acoustic properties. Three varieties of apples were investigated: Golden Delicious, Red Delicious and Granny Smith apples. These apples were bought from a local grocery store. The ultrasonic velocities and attenuation coefficients were determined using dry-coupling through-transmission methods at 250 kHz and 1 MHz. Modulus of Elasticity was also determined for the apples using the Instron universal test machine. The sample length for determining ultrasonic velocities and attenuation coefficients was 7, 12 and 17 mm. The sample length for determining modulus of elasticity was 17 mm. All the measurements were made in longitudinal and radial sections of the apples.

The measurements were made first immediately after the apples were purchased. The same groups of apples were left at room temperature for ten days, and then tested again. Several physical and biochemical changes were associated with the ripening apples: the chlorophyll content of the peel decreased, the tissue softened (decrease in firmness), and some starch was converted into sugars. The experimental results are presented in Appendix C and in Figs. 5.3.12 to 5.3.15. A significant difference was found between the measured ultrasonic parameters of the 'firm' and the 'soft' fruits. For all three varieties, the ultrasonic velocities and elastic moduli decreased as the apples became more ripe. The apparent attenuation coefficient of apple tissues increased after 10 days. Also, the ultrasonic velocity and elastic moduli measured in the radial sections were found to be significantly higher than those in longitudinal sections. These findings suggested that the physical structure and properties of apple tissues are different along these orientations.

5.3.4 Whole Fruit Acoustic Testing System (Objective 4)

Experiments were carried out at the early stage of the study using the Ultrasonic C-scanning system without much success (Chapter 5.2). Only sample tissues cut from potatoes could be tested by this system, using immersion technique with water as couplant. High reflection and attenuation of incident sound waves were observed because of the poor transmission when using both 500 kHz and 1 MHz transducers. The poor penetration was due to insufficient power level of the instrumentation and the type of transducers used. In addition, the system could not be used for test of whole fruits or vegetables, which was one of the primary objectives of this study.

Based on these experiments, a second ultrasonic non-destructive system for whole fruit testing and evaluation was developed. The basic setup included a high-power burst pulser, a broadband receiver, a digital storage oscilloscope and a pair of dry-coupling broadband transducers (Chapter 5.2.1). Since dry-coupling transducers were used, a special device was designed for holding the pair of transducers in line on opposite sides of the test samples. The same amount of pressure could be applied to samples of various size by means of a pressure indicator mounted on the sample holder. The broadband ultrasonic approach was utilized for frequency analysis of the signal. With the experimental system described above, the ultrasound could be successfully transmitted through whole products, such as a whole potato tuber, at the frequency range of up to 1.0 MHz.

Fig. 5.3.12: Changes of ultrasonic velocity in apples

Fig. 5.3.13: Changes of modulus of elasticity in apples

Fig. 5.3.14: Changes of attenuation in apples at 250 kHz

Fig. 5.3.15: Changes of attenuation in apples at 1 MHz

5.4 Evaluation of Research Achievements

The results of this study showed the potential use of ultrasonic testing for identifying fruit and vegetable quality. A method for hollow heart detection in potatoes and further non-destructive quality evaluation of fresh agricultural products could be based on a high power broadband ultrasonic setup and a signal analysis method which have been developed in this study. Before such a system is designed, however, the quality factors for selection must be defined. For example, to design a system to select hollow heart potatoes, one needs to determine the spectrum moment, M_0 , for each tested potato and compare this M_0 value with the criteria value to determine whether to accept or reject the tested potato. This could be accomplished by developing a computer program which takes the output from the acoustic system, makes the appropriate decision, and provides the output for the desired control functions. However, the values of M_0 for different varieties of potatoes would not be the same, and M_0 for each variety would have to be determined experimentally.

The ultrasonic technique was found to be a useful, quick method for evaluating firmness and firmness changes of some fruits and vegetables during storage. Commercial development of this technique may result in improved methods of NDT and quality evaluation. Yet, the transducer coupling conditions for each potato were not consistent and this should be studied further. At 250 kHz, it was difficult to determine the size of a hollow heart in a potato, although the hollow heart could be detected successfully. More research is needed to study the potential applications of transducers with frequencies different from those used in this study. The relationship between measurable ultrasonic parameters and physical parameters of interest such as firmness, maturity, internal quality and defects of fruits and vegetables need to be studied further and quantified for other fruit varieties.

6. DESCRIPTION OF COOPERATION

This research was a joint project of The Technion - I.I.T., The Volcani Center (A.R.O.) and Virginia Polytechnic Institute (V.P.I.). Researchers of the two Israeli institutions worked as a team, in close collaboration; most of the experimental work was done at A.R.O., while the theoretical aspects of the research and analysis of the results were handled mainly at the Technion. Cooperation with the V.P.I. investigators was maintained by phone, E-mail, visits of the Israeli investigators at V.P.I., and several meetings during The ASAE Summer/Winter International Meetings. Details of the Israeli narrow-band testing system were transferred to the V.P.I. co-workers at the early stage of the research. Details of the V.P.I. broad-band experimental system and analysis methods were transferred to the Israeli team. Conclusions of the project were discussed by all partners during the 1992 ASAE Summer Meeting in Charlotte, NC.

In accordance with the specific objective of each of the two countries, firmness and quality parameters of melon and avocado were investigated in Israel, while hollow heart detection in potatoes was studied at V.P.I. The different missions of the two groups have led to different solutions: a broad-band ultrasonic system and frequency analysis method of the transmitted pulse were developed at V.P.I. for the detection of hollow heart in potato, while the narrow-band ultrasonic system was used in Israel for the detection of the ripening process in melon and avocado fruits. The different approach of the two research teams, combined with the close contact and exchange of results maintained among the groups throughout the research work, contributed to widen the scope of the project and increase the potential benefit of its results.

7. SUMMARY AND EVALUATION OF RESEARCH ACHIEVEMENTS

The potential use of ultrasonic measurements in fruits and vegetables was tested and evaluated according to the original research plan. After preliminary testing and verification of basic laws and principles of wave propagation within fruit tissues (Objective 1), the power and frequency range of the ultrasonic system were defined and potential fruits and vegetables were selected for acoustic testing (Objective 2). A systematic study was performed on the relationship between the mechanical and the quality properties of the selected fruits and their response to ultrasonic excitation (Objective 3). The research culminated in the development of an experimental method for whole-fruit detection of hollow heart in potatoes and assessment of internal properties of melons and avocado (Objective 4 of the project).

Most of the previous attempts at ultrasonic testing in fruits and vegetables have failed because of improper frequency range of conventional ultrasonic systems. Results of the first stage of the research have shown that within the frequency range of 50 kHz to 500 kHz and high power excitation amplitude, basic acoustic properties of fruits and vegetables can be detected.

Research continued with the experimental study of relations between acoustical, mechanical and quality parameters of selected fruits. The intensive study of winter-grown melon tissue identified relations between the acoustical attenuation of melon tissue, its degree of ripeness and the sugar content of the tissue samples. The directivity pattern and the attenuation of ultrasonic waves over a half-cut fruit surface were examined as a preliminary step towards whole-fruit testing. The classical directivity pattern in fluids and metals was observed in potato and avocado tissues. Quantitative relations were defined between the ultrasonic transducer and the tested material, which govern the shape of the sound pressure field in the materials. Analysis of the ultrasonic pressure field helped to understand the whole fruit response to ultrasonic excitation.

Local testing of whole melon and avocado fruits was performed using a specially designed ultrasonic head equipped with two inclined probes. Repeated tests with avocado fruit have indicated that changes in sound velocity and attenuation coefficient during the ripening process of the avocado may be used for NDT of maturity and shelf-life determination. Attenuation of the ultrasonic wave correlated well with the color and the estimated ripeness of melons. Further study is needed for verification of the present findings and their application in a commercial, nondestructive testing system.

Assessment of the ultrasonic properties of the tissue specimens, half-cut fruit and whole fruit of melons and avocados was made using narrow-band type transducers. A second ultrasonic non-destructive system for internal defects' identification in whole fruit was developed at V.P.I. The basic setup included a high-power burst pulser, a broad-band receiver and dry-coupling transducers. The broad-band ultrasonic approach was utilized for frequency analysis of the signal. It was found that frequencies higher than 150 kHz could not be transmitted through a whole potato. Frequencies lower than 50 kHz would probably not give enough resolution for detection of hollow hearts in potatoes. Therefore, the frequencies that can be used efficiently to detect hollow hearts in potatoes should be in the range of 50 kHz to 150 kHz. Two varieties of potatoes and three varieties of apples were investigated in this phase of the study. Under the test conditions, all hollow-heart potatoes were identified without any failure. Therefore, the method could provide a way of analyzing the ultrasonic measurements for quantitative NDT of hollow hearts in potatoes.

Although ultrasonic waves could not be transmitted through a whole apple, cylindrical apple tissues were used to investigate its acoustic properties during storage. Several physical and biochemical changes were associated with the ripening process of apples: the chlorophyll content of the peel decreased, the tissue softened (decrease in firmness), and some starch was converted into sugars. A significant difference was found between the measured ultrasonic parameters of the 'firm' and the 'soft' apple. For the tested apple varieties, the ultrasonic velocities and elastic moduli decreased as the apples became riper. The apparent attenuation coefficient of apple tissues increased with storage time.

The results of this study show the potential of using ultrasonic testing to identify fruit and vegetable quality. The ultrasonic technique was found to be a useful, safe and quick method for evaluating firmness and internal defects in some fruits and vegetables. Commercial development of this technique may result in improved methods of NDT for fresh agricultural products. Yet, the

transducer coupling conditions for each fruit were not consistent and should be studied further. In addition, the relationship between measurable ultrasonic parameters and physical parameters of other fruits and vegetables need to be studied further and quantified.

8. LIST OF PUBLICATIONS RESULTING FROM THE RESEARCH PROJECT

8.1 Papers presented at conferences

1. Mizrach, A., N. Galili and G. Rosenhouse. "Determination of fruit and vegetable properties by ultrasonic excitation". ASAE Paper 88-6019, 1988. American Society of Agricultural Engineers, St. Joseph, MI.
2. Mizrach, A., N. Galili, D.C. Teitel and G. Rosenhouse. "Acoustical, mechanical and quality parameters of melon tissue". ASAE Paper No. 893051, 1989. American Society of Agricultural Engineers, St. Joseph, MI.
3. Mizrach, A., N. Galili, G. Rosenhouse and S. Gan-Mor. "Ultrasonic waves as related to impact energy absorbing in melon tissue". ASAE Paper No. 906042, 1990. American Society of Agricultural Engineers, St. Joseph, MI.
4. Mizrach, A., N. Galili and G. Rosenhouse. "Half-cut fruit response to ultrasonic excitation". ASAE Paper No. 923017, 1992. American Society of Agricultural Engineers, St. Joseph, MI.

8.2 Papers in professional journals

1. Mizrach, A., N. Galili. and G. Rosenhouse. "Determination of fruit and vegetable properties by ultrasonic excitation". Transactions of the ASAE, Vol. 32, No. 6, 1989:2053-2058.
3. Mizrach, A., N. Galili, G. Rosenhouse and D.C. Teitel. "Acoustical, mechanical and quality parameters of winter grown melon tissue". Transactions of the ASAE, Vol. 34, No. 5, 1991:2135-2138.
3. Mizrach, A., N. Galili, D.C. Teitel and G. Rosenhouse. "Evaluation of some ripening parameters of autumn- and winter-grown 'GALIA' melons". Submitted to Scientia Horticulturae, 1992, 11 p.

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APPENDICES

APPENDIX-A: Experimental Data of Ettinger Avocado During Storage Period

Table A-1: Acoustical properties of a whole avocado during eight days, 50 kHz excitation frequency

Table A-1: Acoustical properties of a whole avocado during eight days, 50 kHz excitation frequency (continuation)

Table A-2: Acoustical, mechanical and physiological properties of avocado, second group - fruits 1 to 35

Table A-3: Correlation coefficients (R) and probabilities of acoustical, mechanical and physiological parameters of avocado, all tests (40 fruits)

APPENDIX-B: Experimental Data of Yokon-Gold Potatoes During Storage Period

APPENDIX-C: Experimental Results of Apples

APPENDIX-A

Table A-1: Acoustical properties of a whole avocado during eight days, 50 kHz excitation frequency

Acoustical parameters				Data Point	Date	Acoustical parameters				Data Point	Date
R ²	Attenuation α_w (dB/mm)	R ²	Velocity V _w (m/s)			R ²	Attenuation α_w (dB/mm)	R ²	Velocity V _w (m/s)		
0.9877	3.952	0.9988	382.7	A1	23/11/92	0.987	3.008	0.9985	335.62	A1	19/11/92
0.9919	4.138	0.9981	420.38	A2		0.9985	3.317	0.995	342.07	A2	
0.999	4.633	0.9996	324.4	A3		0.9573	3.021	0.9924	320.37	A3	
0.9779	4.494	0.9961	362.99	A4		0.977	3.021	0.9958	288.16	A4	
0.9765	4.127	0.9966	438.29	B1		0.988	2.348	0.9952	347.73	B1	
0.998	5.244	0.993	373.8	B2		0.9797	2.142	0.9962	373.47	B2	
0.9893	5.322	0.9996	383.89	B3		0.9931	2.705	0.9981	333.67	B3	
0.9999	5.787	0.9628	425.84	B4		0.9813	2.554	0.9973	317.33	B4	
0.9992	3.954	0.9944	255.73	C1		0.9912	2.387	0.9921	360.58	C1	
0.9627	5.236	0.9949	328.68	C2		0.9713	2.835	0.9837	324.88	C2	
0.9817	4.508	0.9593	172.85	C3		0.9819	2.699	0.9974	324.99	C3	
0.9882	3.619	0.9977	350.78	C4		0.99	2.556	0.988	357.94	C4	
0.9851	4.503	0.9915	331.12	D1		0.9783	2.659	0.9295	373.96	D1	
0.9998	4.472	1	327.81	D2		0.9919	2.86	0.9951	330.6	D2	
0.9913	3.196	1	349.31	D3		0.9762	2.716	0.9992	345.15	D3	
0.9971	4.55	1	290.97	D4		0.9783	2.659	0.9295	373.96	D4	
0.9953	3.679	0.9893	231.15	E1		0.9665	2.74	0.9942	320.33	E1	
0.9997	4.743	0.9984	298.29	E2		0.998	2.761	0.9968	368.41	E2	
0.9917	4.072	0.9862	230.27	E3		0.9918	2.548	0.9976	336.62	E3	
0.998	4.083	0.9869	215.86	E4		0.997	3.005	0.9999	319.65	E4	
0.9466	4.234	0.9893	397.44	A1	24/11/92	0.9851	4.084	0.9973	322.57	A1	20/11/92
0.9402	4.385	0.999	405.82	A2		0.9957	3.968	0.9983	342.18	A2	
0.9972	6.364	0.9949	349.06	A3		0.9834	4.372	0.9951	376.73	A3	
0.9916	3.699	0.9996	423.68	A4		0.9897	3.862	0.9943	281.55	A4	
0.99	5.822	0.994	350.21	B1		0.999	3.845	0.993	251.31	B1	
0.9905	3.827	0.9959	431.42	B2		0.9687	3.045	0.9958	307.92	B2	
0.9982	4.994	0.9984	422.65	B3		0.9937	3.234	0.9951	319.55	B3	
0.913	4.064	0.9801	438.31	B4		0.9991	3.033	0.9954	277.81	B4	
0.9954	4.363	0.9995	265.29	C1		0.9925	3.21	0.9833	307.02	C1	
0.9722	5.748	0.99	320.35	C2		0.9767	3.783	0.9964	318.06	C2	
0.9722	3.556	0.9939	329.96	C3		0.9979	3.206	0.9933	303.97	C3	
0.9784	4.736	0.9892	366.6	C4		0.99	3.348	0.997	352.68	C4	
0.9986	5.071	1	296.88	D1		0.9899	3.843	0.9954	277.34	D1	
0.9873	4.127	0.9994	347.98	D2		0.992	3.913	0.9998	352.82	D2	
0.9991	4.457	1	317.29	D3		0.972	4.099	0.9938	298.77	D3	
0.9882	4.105	0.9999	333.17	D4		0.9903	3.538	1	325.29	D4	
0.9934	3.549	0.9955	257	E1		0.9904	3.498	0.999	286.76	E1	
0.9936	6.427	0.9998	305.29	E2		0.9904	3.498	0.999	286.76	E2	
0.9954	3.838	0.9961	297.96	E3		0.9932	2.643	1	328.21	E3	
0.9792	4.009	0.9905	291.69	E4		0.9965	3.699	0.9979	266.85	E4	

Table A-1: Acoustical properties of a whole avocado during eight days, 50 kHz excitation frequency (continuation)

Acoustical parameters				Data Point	Date
R ²	Attenuation α_w (dB/mm)	R ²	Velocity V _w (m/s)		
-	-	-	-	A1	25/11/92
0.9997	5.16	0.9994	377.52	A2	
0.9992	5.196	0.9994	400.29	A3	
0.9744	3.662	0.9975	363.34	A4	
0.9939	5.3	0.9585	449.14	B1	
-	-	-	-	B2	
0.982	4.344	0.9581	461.99	B3	
0.9097	4.406	0.9699	596.77	B4	
0.9947	3.919	0.9939	403.8	C1	
0.9994	5.313	0.9996	328.51	C2	
0.9958	5.628	1	323.13	C3	
0.9849	4.378	0.9994	336.06	C4	
0.9979	5.916	0.9799	376.29	D1	
0.9954	4.327	0.9976	416.77	D2	
0.9996	4.794	0.9947	391.63	D3	
0.9946	4.839	1	335.02	D4	
0.9994	3.738	0.9948	364.95	E1	
0.9983	5.05	0.9878	355.9	E2	
1	4.712	0.991	345.4	E3	
0.9999	4.946	0.9896	343.21	E4	
-	-	-	-	A1	26/11/92
0.9992	4.067	0.9855	407.03	A2	
0.9943	4.193	0.9986	359.6	A3	
0.9606	4.692	0.9986	360.24	A4	
0.999	4.494	1	444.01	B1	
-	-	-	-	B2	
0.9423	4.667	0.9683	460.06	B3	
0.843	3.392	0.9942	403.48	B4	
0.9869	4.794	0.9981	343.58	C1	
0.9753	3.812	0.9976	417.74	C2	
0.9912	4.435	0.989	367.39	C3	
0.9893	3.487	0.9958	410.19	C4	
0.9997	4.859	0.9998	346.75	D1	
0.9982	4.936	0.9988	396.4	D2	
0.9992	5.561	0.9981	343.35	D3	
1	5.339	0.9983	341.16	D4	
0.995	6.074	1	386.35	E1	
0.9989	4.763	0.9955	424.95	E2	
0.9971	6.657	0.9805	385.9	E3	
0.9895	5.69	0.9899	326.58	E4	
0.9982	4.211	0.9911	348.24	A1	21/11/92
0.9982	4.211	0.9911	348.24	A2	
0.9998	4.435	0.9719	231.95	A3	
0.9159	2.958	0.9924	237.58	A4	
0.9981	3.077	0.9949	267.88	B1	
0.9974	3.416	0.9847	269.06	B2	
0.9742	2.845	0.9919	267.03	B3	
0.983	2.804	0.9988	264.26	B4	
0.9995	3.727	0.997	262.11	C1	
0.9971	3.679	0.9984	318.94	C2	
0.9984	3.465	0.9876	264.15	C3	
0.9804	3.723	0.9982	343.17	C4	
0.9819	3.009	0.9896	243.47	D1	
0.9999	4.077	0.9997	300.84	D2	
0.9852	4.214	0.9865	270.7	D3	
0.9914	3.78	0.9988	332.16	D4	
0.9811	3.075	0.9869	281.82	E1	
0.9906	4.037	0.9974	291.27	E2	
0.9942	3.989	0.9985	269.06	E3	
0.9822	3.468	0.9968	215.52	E4	
0.9977	4.125	0.9923	346.22	A1	22/11/92
0.9997	3.945	0.987	351.58	A2	
0.9802	3.953	0.9816	246.83	A3	
0.9867	4.447	0.9922	369.02	A4	
0.9946	3.043	0.9956	297.03	B1	
0.9406	3.047	0.9929	367.23	B2	
0.9936	4.303	0.9996	315.4	B3	
0.999	3.582	1	258.77	B4	
0.9916	3.369	0.999	284.66	C1	
0.9774	4.472	0.9972	303.09	C2	
0.9968	4.174	0.9896	253.04	C3	
0.9672	3.652	0.9927	351.74	C4	
0.9956	4.245	0.9855	246.22	D1	
0.9999	4.071	0.9973	324.58	D2	
0.9948	3.854	0.999	311.37	D3	
0.9793	4.482	0.9999	316.56	D4	
0.999	3.644	0.9973	269.65	E1	
0.9843	4.356	0.9954	284.43	E2	
1	4.224	0.9871	247.99	E3	
0.9968	3.66	0.9907	239.48	E4	

Table A-2: Acoustical, mechanical and physiological properties of avocado, second group - fruits 1 to 35

Physiological	Acoustical parameters				Mechanical parameters		Time (h)	Fruit No. (h)
Dry weight (%)	Attenuation, α_t (dB/mm)	Velocity, V_t (m/s)	Attenuation, α_w (dB/mm)	Velocity, V_w (m/s)	E-modulus (MPa)	Firmness, F (N)		
30.99	4.034	274.5	3.003	278.76	3.1827	65.5	24	1
31.99	3.062	160.3	3.264	291.74	2.3796	61.0	24	2
26.58	4.538	216.0	3.403	242.41	3.5861	76.5	24	3
27.64	3.593	227.6	3.640	312.71	2.9606	65.5	24	4
24.32	2.833	310.9	2.833	310.90	3.0311	54.5	24	5
28.96	4.168	190.2	2.710	332.41	3.1827	72.0	48	6
28.85	4.726	266.6	2.976	238.82	3.0676	76.0	48	7
31.98	4.694	199.4	3.052	324.76	2.4962	57.5	48	8
27.83	4.519	264.0	3.432	328.54	2.7980	59.0	48	9
33.57	4.119	221.6	3.138	342.37	2.7378	56.5	48	10
33.97	4.444	231.9	3.579	364.28	2.4249	48.0	72	11
34.68	3.400	320.8	4.169	383.63	4.420	50.0	72	12
30.64	5.000	213.8	3.193	244.13	3.0676	54.0	72	13
29.76	5.158	214.2	3.091	284.84	3.0676	62.0	72	14
29.38	5.316	227.2	2.601	225.71	2.5461	49.5	72	15
29.80	4.104	258.4	4.142	415.21	4.301	15.0	96	16
38.49	4.207	212.5	4.216	286.54	2.6522	52.0	96	17
28.95	4.681	216.6	3.066	228.45	2.8608	60.0	96	18
31.82	4.536	217.2	4.069	311.19	3.1827	62.0	96	19
31.74	4.706	238.6	2.411	319.53	3.2643	55.0	96	20
30.02	4.529	263.3	4.184	327.44	3.1051	57.5	120	21
25.05	4.378	274.2	4.099	346.83	1.4304	26.0	120	22
30.48	5.373	188.5	4.221	206.68	3.1827	69.0	120	23
29.98	4.403	223.3	3.936	331.57	2.9606	58.0	120	24
37.29	4.136	327.7	4.136	367.82	0.3459	3.0	120	25
32.59	3.974	379.2	2.545	483.68	0.3881	5.0	144	26
25.96	3.429	291.7	5.274	290.27	0.5052	5.5	144	27
31.14	4.158	294.6	3.855	411.37	0.3536	3.0	144	28
31.68	3.339	297.6	3.595	421.72	0.5052	5.0	144	29
27.78	4.733	366.9	4.369	236.88	1.5913	49.0	144	30
24.82	4.451	260.3	3.715	232.20	0.2567	2.0	168	31
31.60	4.000	333.3	4.210	384.89	0.3744	2.5	168	32
26.41	4.461	246.3	3.741	242.36	1.2241	10.0	168	33
30.37	3.838	330.3	4.668	359.30	0.5535	3.0	168	34
28.66	5.476	601.1	3.271	419.70	0.2842	2.5	168	35

Table A-3: Correlation coefficients (R) and probabilities of acoustical, mechanical and physiological parameters of avocado, all tests (40 fruits)

	Time	Firm	E-modulus	Vw	aw	Vt	at	DW %	Vp	ap
Time	1.00000	-0.81399	-0.75905	0.44938	0.68320	0.53031	0.13270	0.04072	0.73684	1.00000
	0.0000	0.0001	0.0001	0.0001	0.0001	0.0015	0.4616	0.8220	0.0001	0.0000
	189	33	32	184	186	33	33	33	189	189
Firm	-0.81399	1.00000	0.97870	-0.77322	-0.52737	-0.64127	0.20365	-0.03127	-0.82821	-0.81399
	0.0001	0.0000	0.0001	0.0001	0.0028	0.0001	0.2556	0.8629	0.0001	0.0001
	33	33	32	30	30	33	33	33	33	33
E modulus	-0.75905	0.97870	1.00000	-0.79560	-0.50484	-0.62818	0.24308	-0.04058	-0.78471	-0.75905
	0.0001	0.0001	0.0000	0.0001	0.0052	0.0001	0.1801	0.8255	0.0001	0.0001
	32	32	32	29	29	32	32	32	32	32
Vw	0.44938	-0.77322	-0.79560	1.00000	0.26804	0.59234	-0.30762	0.23523	0.60755	0.44938
	0.0001	0.0001	0.0001	0.0000	0.0003	0.0006	0.0982	0.2108	0.0001	0.0001
	184	30	29	184	181	30	30	30	184	184
aw	0.68320	-0.52737	-0.50484	0.26804	1.00000	0.14665	-0.16463	0.13534	0.42359	0.68320
	0.0001	0.0028	0.0052	0.0003	0.0000	0.4393	0.3846	0.4758	0.0001	0.0001
	186	30	29	181	186	30	30	30	186	186
Vt	0.53031	-0.64127	-0.62818	0.59234	0.14665	1.00000	0.00711	-0.05542	0.56108	0.53031
	0.0015	0.0001	0.0001	0.0006	0.4393	0.0000	0.9687	0.7594	0.0007	0.0015
	33	33	32	30	30	33	33	33	33	33
at	0.13270	0.20365	0.24308	-0.30762	-0.16463	0.00711	1.00000	-0.01910	-0.04259	0.13270
	0.4616	0.2556	0.1801	0.0982	0.3846	0.9687	0.0000	0.9160	0.8139	0.4616
	33	33	32	30	30	33	33	33	33	33
%DW	0.04072	-0.03127	-0.04058	0.23523	0.13534	-0.05542	-0.01910	1.00000	-0.06445	0.04072
	0.8220	0.8629	0.8255	0.2108	0.4758	0.7594	0.9160	0.0000	0.7216	0.8220
	33	33	32	30	30	33	33	33	33	33
Vp	0.73684	-0.82821	-0.78471	0.60755	0.42359	0.56108	-0.04259	-0.06445	1.00000	0.73684
	0.0001	0.0001	0.0001	0.0001	0.0001	0.0007	0.8139	0.7216	0.0000	0.0001
	189	33	32	184	186	33	33	33	189	189
ap	1.00000	-0.81399	-0.75905	0.44938	0.68320	0.53031	0.13270	0.04072	0.73684	1.00000
	0.0000	0.0001	0.0001	0.0001	0.0001	0.0015	0.4616	0.8220	0.0001	0.0000
	189	33	32	184	186	33	33	33	189	189

Where; PEARSON CORRELATION COEFFICIENTS / PROB > |R| UNDER H0:RHO=0 / N

APPENDIX-B

**Experiment data of Yukon-Gold potatoes
During Storage Period**

Notations used in this appendix:

- V_m = velocity determined using 1 MHz transducers, m/s
- V_k = velocity determined using 250 kHz transducers, m/s
- V = velocity determined using the both transducers, m/s
- E = modulus of elasticity, MPa
- F_M = maximum force at rapture point, N
- α_m = apparent attenuation coefficient determined using 1 MHz transducers, dB/mm
- α_k = apparent attenuation coefficient determined using 250 kHz transducers, dB/mm

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Transverse measurements

V_m	V_k	V	E	F_M	α_m	α_k
631.44	619.58	625.45	3.98	455.60	1.475	1.548
675.07	674.03	674.55	3.74	431.15	1.721	1.694
670.18	683.11	676.58	3.68	620.60	1.603	1.659
631.78	619.34	625.50	3.44	618.20	1.779	1.791
668.30	661.95	665.11	3.27	501.00	1.822	1.995
628.80	597.72	612.86	3.33	514.60	1.655	1.810
573.12	573.48	573.30	2.75	431.60	2.034	1.762
624.45	618.57	621.49	3.21	420.90	1.815	1.861
691.00	706.06	698.47	3.31	502.90	1.562	1.701
624.90	606.38	615.50	2.81	446.80	1.590	1.727
<hr/>						
Avg= 641.90	636.02	638.88	3.35	494.33	1.706	1.727
Var= 1190.60	1816.65	1457.65	0.15	5429.98	0.027	0.029
(Var is sample variance, and is standard deviation squared)						

Longitudinal measurements

V_m	V_k	V	E	F_M	α_m	α_k
672.00	662.69	667.31	4.15	523.40	1.583	1.646
717.17	696.08	706.47	3.92	482.90	1.778	1.632
683.17	693.47	688.28	3.69	507.80	1.381	1.956
574.87	598.23	586.32	3.57	506.30	1.573	1.657
552.91	552.47	552.69	2.74	524.90	1.652	1.637
659.62	676.13	667.77	4.20	490.20	1.614	1.842
714.36	680.17	696.85	4.28	527.30	1.500	1.499
599.16	617.92	608.39	4.21	473.10	1.789	1.544
664.96	649.24	657.01	3.88	512.70	1.701	1.913
636.55	611.94	624.01	4.12	498.50	1.829	1.939
<hr/>						
Avg= 647.48	643.83	645.51	3.88	504.71	1.640	1.727
Var= 3147.51	2228.60	2582.59	0.22	340.79	0.020	0.029

Group II 10/22/91

Transverse measurements

V_m	V_k	V	E	F_M	α_m	α_k
647.26	647.73	647.49	3.19	554.20	1.552	1.666
607.76	602.47	605.10	3.31	521.00	1.514	1.627
653.63	680.44	666.77	3.25	443.40	1.359	1.571
643.52	636.88	640.18	3.26	517.60	1.328	1.483
702.77	727.87	715.10	3.18	533.20	1.929	2.121
663.51	660.02	661.76	3.19	463.90	1.835	1.942
704.81	677.71	690.99	3.75	555.70	1.541	1.465
620.37	641.15	630.59	2.60	440.10	1.262	1.467
687.57	697.56	692.53	3.33	477.10	1.298	1.392
752.11	764.12	758.07	4.52	588.40	1.585	1.499
<hr/>						
Avg= 668.33	673.60	670.86	3.36	509.46	1.520	1.623
Var= 1908.21	2232.37	1996.73	0.24	2603.55	0.050	0.055

Longitudinal measurements

V_m	V_k	V	E	F_M	α_m	α_k
749.37	695.95	721.67	3.97	532.70	1.653	1.635
724.20	709.33	716.69	3.90	544.90	1.714	1.236
694.64	758.37	725.11	4.32	524.90	1.535	1.690
674.66	696.87	685.59	4.13	539.10	1.243	1.612
636.60	638.94	637.77	4.04	485.40	1.631	1.558
622.95	613.02	617.95	3.55	553.20	1.543	1.755
600.45	623.03	611.53	3.75	436.50	1.571	1.463
648.87	643.55	646.20	3.61	475.60	1.552	1.516
688.42	696.07	692.22	3.76	450.00	1.755	1.855
725.14	714.93	720.01	4.21	413.10	1.470	1.528
<hr/>						
Avg= 676.53	679.01	677.47	3.92	495.54	1.567	1.585
Var= 2381.37	2195.11	2033.24	0.07	2528.65	0.021	0.029

Group III 11/19/91

Transverse measurements

V_m	V_k	V	E	F_M	α_m	α_k
852.10	832.37	842.11	3.29	460.00	1.011	1.562
729.22	706.92	717.90	3.75	498.04	1.633	1.623
683.93	697.10	690.45	3.23	466.00	1.510	1.359
669.83	676.61	673.20	3.57	496.01	1.745	1.558
682.48	651.91	666.85	3.53	521.50	1.818	1.722
640.67	631.86	636.23	3.83	523.40	1.614	1.635
661.59	650.69	656.09	4.13	514.60	1.172	1.210
639.64	623.62	631.53	3.45	458.00	1.227	1.473
651.41	652.53	651.97	3.03	518.10	1.909	1.744
750.16	735.95	742.97	3.90	510.25	1.210	1.429
<hr/>						
Avg= 696.10	685.96	690.93	3.57	496.59	1.485	1.532
Var= 4314.17	3879.97	4048.61	0.11	675.46	0.096	0.028

Longitudinal measurements

V_m	V_k	V	E	F_M	α_m	α_k
731.54	709.01	720.10	4.16	537.10	1.528	1.302
681.35	662.68	671.88	4.34	530.30	1.556	1.356
576.94	634.13	604.19	3.88	507.30	1.534	2.070
681.26	682.63	681.94	4.13	547.40	1.480	1.573
671.53	674.72	673.12	4.18	619.60	1.883	1.853
742.84	746.05	744.44	3.87	479.50	1.359	1.288
691.94	747.02	718.43	3.88	523.90	1.577	1.338
748.98	735.05	741.95	4.05	502.00	1.630	1.701
726.71	702.09	714.19	4.26	500.00	1.529	1.486
669.95	676.62	673.27	3.63	438.50	1.576	1.595
<hr/>						
Avg= 692.30	697.00	694.35	4.04	518.56	1.521	1.556
Var= 2552.39	1419.40	1788.24	0.05	2247.96	0.018	0.067

Group IV 12/17/91

Transverse measurements

V_m	V_k	V	E	F_M	α_m	α_k
701.52	691.62	696.53	3.56	493.20	1.648	1.577
664.77	653.35	659.01	3.88	508.30	1.069	1.556
768.97	751.53	760.15	4.58	555.17	1.406	1.365
716.97	698.89	707.82	3.54	410.60	1.480	1.546
659.22	619.77	638.89	3.89	467.30	1.147	1.343
727.07	715.22	721.10	3.80	549.30	1.589	1.467
737.34	731.79	734.56	3.75	444.30	1.375	1.407
699.93	696.37	698.15	3.17	390.60	1.525	1.343
718.12	751.28	734.33	3.43	407.20	1.538	1.863
732.79	696.93	714.41	3.99	514.60	1.516	1.585
<hr/>						
Avg= 712.67	700.68	706.50	3.76	474.06	1.429	1.473
Var= 1097.40	1692.20	1301.47	0.14	3535.16	0.035	0.025

Longitudinal measurements

V_m	V_k	V	E	F_M	α_m	α_k
533.17	536.42	534.79	4.10	534.70	1.379	1.267
672.29	682.69	677.45	4.21	477.05	1.602	1.508
781.00	781.00	781.00	4.63	555.17	1.364	1.281
780.53	802.94	791.58	4.48	437.01	1.069	0.990
775.97	785.57	780.74	3.70	505.40	1.853	1.941
808.68	798.75	803.69	4.82	537.10	1.537	1.708
679.74	701.02	690.22	3.91	479.00	1.489	1.460
786.03	769.42	777.64	3.95	436.50	1.675	1.863
591.84	563.53	577.34	4.55	518.60	1.132	1.763
694.32	718.92	706.00	5.10	478.03	1.223	1.108
<hr/>						
Avg= 710.36	714.03	712.05	4.35	495.86	1.432	1.489
Var= 8633.20	9236.04	8863.95	0.20	1697.56	0.061	0.106

Group V 1/14/92

Transverse measurements

V_m	V_k	V	E	F_M	α_m	α_k
621.41	632.08	626.70	4.13	452.84	1.976	1.634
631.37	631.14	631.25	3.12	482.70	1.379	1.307
736.89	726.12	731.47	4.26	676.54	1.551	1.415
726.36	714.19	720.23	3.39	529.39	1.584	1.625
560.22	579.45	569.68	3.56	465.30	1.077	1.361
758.93	758.69	758.81	3.63	486.50	1.133	1.672
671.79	682.84	677.27	3.81	483.24	1.380	1.559
762.71	797.64	779.78	4.19	584.78	1.505	1.580
720.94	708.75	714.79	3.43	456.09	1.659	1.597
668.00	678.64	673.54	3.72	450.66	1.587	1.503
<hr/>						
Avg= 685.86	690.95	688.35	3.72	506.80	1.483	1.525
Var= 4460.60	4195.31	4264.96	0.14	5256.44	0.068	0.016

Longitudinal measurements

V_m	V_k	V	E	F_M	α_m	α_k
596.38	607.02	601.65	3.90	400.71	1.433	1.627
624.66	616.36	620.48	3.62	484.87	1.283	1.114
722.68	741.46	731.95	4.65	612.47	1.331	1.172
753.59	741.67	747.58	4.03	489.76	1.297	1.590
736.07	751.35	743.63	4.14	471.84	1.945	1.588
654.54	613.11	633.15	4.07	545.68	1.390	1.676
794.53	789.90	792.21	4.31	582.60	1.795	1.796
808.21	817.60	812.88	4.53	548.94	1.539	1.548
777.06	756.34	766.56	4.24	430.57	1.672	1.557
604.17	596.68	600.40	3.38	453.38	1.246	1.408
<hr/>						
Avg= 706.19	703.15	705.05	4.09	502.08	1.493	1.508
Var= 6490.81	7216.09	6777.04	0.15	4654.43	0.057	0.047

Group VI 2/11/92

Transverse measurements

	V_m	V_k	V	E	F_M	α_m	α_k
	669.74	649.79	659.71	3.37	487.04	1.939	1.612
	695.88	689.19	692.52	3.94	508.22	1.173	1.231
	619.04	629.23	624.09	3.53	431.12	1.217	1.220
	639.93	619.77	629.69	3.42	390.94	1.136	1.674
	619.12	608.41	613.72	3.81	470.21	1.761	1.628
	800.87	782.97	791.82	3.68	441.43	1.126	1.196
	787.33	786.55	786.94	4.06	552.74	1.153	1.151
	748.86	778.27	762.76	4.23	563.60	1.259	0.987
	829.77	765.98	796.60	3.76	516.36	1.208	1.188
	606.62	611.07	608.84	3.18	471.84	1.242	1.641
Avg=	701.72	692.12	696.67	3.70	483.35	1.321	1.353
Var=	7039.60	6068.27	6365.37	0.11	2922.98	0.081	0.065

Longitudinal measurements

	V_m	V_k	V	E	F_M	α_m	α_k
	777.25	737.93	757.08	4.31	533.73	1.353	1.431
	678.93	661.13	669.91	3.96	500.07	0.781	1.151
	609.15	614.44	611.78	3.72	450.66	1.664	1.794
	656.79	651.20	653.98	3.98	512.02	1.311	1.399
	882.65	851.02	866.55	4.54	551.66	1.420	1.418
	700.99	690.70	695.81	4.11	470.21	1.477	1.784
	700.85	670.77	685.48	4.00	583.15	1.526	1.438
	767.44	735.79	751.28	4.21	548.94	1.163	1.381
	702.69	688.95	695.75	3.76	498.99	1.026	1.309
	715.04	730.24	722.56	4.00	471.30	1.082	1.308
Avg=	719.18	703.22	711.02	4.06	512.07	1.280	1.441
Var=	5666.52	4290.38	4886.01	0.06	1772.11	0.071	0.041

APPENDIX-C

Experiment Results of Apples

Notations used in this appendix:

- V_l = ultrasonic velocity measured in longitudinal sections
- V_r = ultrasonic velocity measured in radial sections
- E_l = modulus of elasticity measured in longitudinal sections
- E_r = modulus of elasticity measured in radial sections
- α_{lm} = apparent attenuation coefficient measured in longitudinal sections using 1 MHz transducers
- α_{rm} = apparent attenuation coefficient measured in radial sections using 1 MHz transducers
- α_{lk} = apparent attenuation coefficient measured in longitudinal sections using 250 KHz transducers
- α_{rk} = apparent attenuation coefficient measure in radial sections using 250 Khz transducers

GRANNY SMITH APPLES

Longitudinal Measurements				Radial Measurements			
V_l	E_l	α_{lm}	α_{lk}	V_r	E_r	α_{rm}	α_{rk}
137.35	3.57	1.704	1.687	217.19	6.41	1.631	1.402
130.56	4.17	1.649	1.250	264.19	5.54	2.335	1.810
123.43	3.75	1.417	0.958	206.34	6.56	2.247	2.007
142.77	3.84	2.139	1.708	265.57	5.83	1.523	1.371
142.31	3.44	2.856	1.606	247.75	6.34	1.470	0.703
124.07	3.57	1.732	1.453	199.44	6.21	1.449	1.008
AVG= 133.42	3.72	1.916	1.444	233.41	6.15	1.776	1.384
VAR= 75.46	0.07	0.266	0.086	867.43	0.15	0.164	0.235

10 DAYS LATER

95.94	3.08	2.379	1.230	197.14	4.61	1.861	1.465
116.45	3.05	2.235	1.698	195.04	4.66	2.403	2.087
111.05	3.32	1.953	1.439	188.43	4.72	2.201	1.646
118.29	3.60	2.994	2.626	215.45	4.67	2.887	2.443
114.18	3.35	3.346	2.500	199.20	5.20	3.246	2.072
119.37	3.03	2.831	2.700	179.95	4.41	1.938	1.894
AVG= 112.55	3.24	2.623	2.032	195.87	4.71	2.423	1.935
VAR= 75.09	0.05	0.273	0.425	141.11	0.07	0.299	0.121

RED DELICIOUS APPLES

Longitudinal Measurements				Radial Measurements			
V_l	E_l	α_{lm}	α_{lk}	V_r	E_r	α_{rm}	α_{rk}
154.72	4.65	2.416	1.935	237.78	6.20	1.683	1.573
137.91	4.49	2.076	1.833	254.47	5.60	0.738	0.494
123.33	3.78	1.388	1.357	199.09	5.20	2.070	1.759
134.82	3.91	1.665	1.420	212.06	6.06	1.294	1.148
134.36	3.74	1.989	1.395	210.05	5.19	1.650	1.477
160.47	3.75	1.507	1.448	228.77	5.83	1.521	1.488
AVG= 140.94	4.05	1.840	1.565	223.70	5.68	1.493	1.323
VAR= 194.27	0.17	0.151	0.063	419.64	0.18	0.201	0.204

10 DAYS LATER

125.21	3.63	2.623	1.284	189.16	4.03	1.894	1.771
107.43	2.69	1.786	1.704	179.23	3.90	2.224	1.673
126.97	3.08	2.581	2.477	181.58	4.68	1.192	1.149
107.21	2.97	3.818	3.586	188.08	4.65	2.198	2.031
116.97	2.70	2.483	2.263	169.10	3.96	2.860	2.457
122.31	2.61	2.253	2.224	186.06	4.51	2.659	2.390
AVG= 117.68	2.93	2.591	2.256	182.20	4.29	2.171	1.912
VAR= 75.93	0.12	0.456	0.614	55.75	0.13	0.350	0.240

GOLDEN DELICIOUS APPLES

Longitudinal Measurements				Radial Measurements			
V_l	E_l	α_{lm}	α_{lk}	V_r	E_r	α_{rm}	α_{rk}
125.98	3.11	2.845	2.734	174.64	4.64	1.586	1.121
136.83	3.25	1.982	1.861	186.98	4.00	2.264	2.410
130.46	3.21	2.717	2.104	200.65	3.87	1.628	1.501
122.87	3.09	2.351	1.958	231.51	3.89	2.186	2.176
124.69	3.12	2.780	2.331	167.18	3.92	1.202	1.156
130.27	3.41	2.368	2.148	244.08	4.23	1.423	1.300
111.59	3.86	1.664	1.262	179.47	4.56	1.018	0.887
AVG= 126.10	3.29	2.387	2.057	197.79	4.16	1.615	1.507
VAR= 62.42	0.07	0.194	0.204	868.89	0.11	0.219	0.327

10 DAYS LATER

107.21	2.39	2.826	2.333	129.16	2.74	2.146	2.078
91.41	3.09	2.642	2.256	129.05	3.27	2.037	1.918
101.55	2.66	4.642	3.822	155.97	3.57	2.294	1.538
96.32	2.96	3.246	3.007	125.93	3.69	2.814	2.044
98.61	2.75	2.397	2.248	168.97	3.24	2.849	2.830
88.74	2.18	2.379	2.314	129.23	3.30	2.768	2.443
105.22	2.97	2.439	2.091	157.86	4.03	1.722	1.484
AVG= 98.44	2.71	2.939	2.582	142.31	3.41	2.376	2.048
VAR= 46.76	0.11	0.659	0.385	321.22	0.17	0.195	0.227