WATERMELON MATURITY DETERMINED FROM IMPULSE FREQUENCY RESPONSE

By

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IMPULSE FREQUENCY RESPONSE

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NOMENCLATURE

Avg F.	Average firmness for PT1, PT2, PH, kg
Avg R.	Average optical refraction for ST1, ST2, SH, Rdiv
CFN50	Center frequency of the narrowest 50 percent energy band Hz
EB85-160	Ratio of spectrum energy for the frequency band 85-160 Hz
Minor	Diameter of minor axis, cm
Major	Diameter of major axis, cm
MF8	Average slope of penetration force versus penetration depth for 8 mm, kg/cm
MF20	Average slope of penetration force versus penetration depth for 20 mm, kg/cm
MF40	Average slope of penetration force versus penetration depth for 40 mm, kg/cm
p8	Average peak force for 8 mm, kg
p20	Average peak force for 20 mm, kg
p40	Average peak force for 40 mm, kg
PRT	Average penetrometer reading for Rind-tissue, kg
PT1	Average penetrometer reading of Tissue 1, kg
PT2	Average penetrometer reading of Tissue 2, kg
PH	Average penetrometer reading of Heart, kg
Rdiv	Divisions of the optical refractometer scale
rind	Outer skin covering of watermelon approximately 1 mm thick. "rind" refers to the outer white tissue region including the rind, approximately 10-30 mm thick depending on maturity
SRT	Average optical refraction of Rind-tissue, Rdiv
ST1	Average optical refraction of Tissue 1, Rdiv
ST2	Average optical refraction of Tissue 2, Rdiv
SH	Average optical refraction of Heart, Rdiv
Sub Mat.	Subjective maturity rating
Wt	Weight of the watermelon, kg

CHAPTER I

INTRODUCTION

Watermelon is one of the more important vegetable crops in Oklahoma. Approximately 9,000 to 15,000 acres per year of watermelons are planted in Oklahoma, worth more than $4 million dollars to the Oklahoma farmers (McCraw 1991). Quality and maturity is an important issue with watermelons, as it is for all fresh fruits. An increase in the quality of fruits in the market place increases the demand and likewise the price of the product.

Quality and texture of a watermelon are highly dependent upon the state of maturity of the melon. When a watermelon is picked too early the inner tissue is not as sweet and tends to be firmer than when the melon is picked at optimum maturity. Watermelons do not mature significantly after being removed from the vine and under normal storage conditions do not degrade significantly for about two to three weeks. Therefore, watermelons should be picked during peak maturity for optimum taste and quality. The time window during which a watermelon is at peak maturity depends on growing conditions and variety, but lasts approximately three days.

For highest market value, the goal of the watermelon producer is to pick watermelons during the peak maturity period. Maturity of a watermelon is not easily determined by outward characteristics. It must be done by experienced personnel. Pickers in the field are typically capable of determining watermelon maturity, but they are prone to bias in judgement, inexperience, and pressure to meet the market demand.

Maturity determination of watermelons has traditionally been done by observing several qualitative parameters and then making a subjective decision. Parameters used for such subjective testing include: color of the watermelon rind, width of the stripes (for a striped watermelon), sound the watermelon makes when thumped with a finger, and comparison of size and shape to melons that are known to be ripe. For an experienced picker in the field, who has the benefit of checking one or two of his decisions by cutting the watermelons open, subjective testing can be accurate. However, for the inexperienced buyer or produce manager who must check several different cultivars in the market place, judgement is far less accurate.

To help increase overall quality of watermelons found in the market, an objective testing method is needed that can be used by producers, retailers, and consumers. The testing method needs to be non-destructive, and should not require extensive experience.

Objective

The objective of this research was to develop a non-destructive technique for measuring watermelon maturity. Operationally, the work was focused to meet the following objectives:

1. To develop an impulse frequency response sensor sensitive to vibration levels of a watermelon.
2. To determine characteristics of the impulse frequency response that are correlated to maturity.

Both objectives are based upon the use of impulse testing as a non-destructive method of testing watermelon maturity. Impulse testing is done by applying a pulse of energy to a specimen and then measuring the resulting vibrations of the specimen. The resulting vibrations are referred to as the impulse frequency response. Characteristics of either the time domain or frequency domain (spectrum) of the impulse frequency response could be searched for correlation to maturity.

Organization of Thesis

Chapter II presents a review of the literature on using frequency response testing of fruit and vegetables to measure texture, quality, and maturity. Chapter III contains a discussion of the equipment used to measure the frequency response of watermelons, and the design of the impulse sensor unit used for this study. Chapter IV presents the experiment layout, and the methods used for measuring the maturity of watermelons. The final chapter presents the results of this study and discusses some recommendations for further research.

CHAPTER II

LITERATURE REVIEW

Literature on non-destructive testing methods to measure fruit quality has shown some promise for acoustical methods in maturity determination of apples, peaches, and melons. In the literature, most researchers used either attenuation or natural frequency to correlate measured acoustic signals and quality of the specimens.

Maturity of the watermelons in this study was based upon destructive measured parameters of the melon tissue. The literature contains very little concrete information on destructively measured physical properties that are good predictors of maturity. However, some measurable parameters that other researchers have used include: color of the inner melon tissue, sugar content of the tissue, firmness or texture of the tissue, thickness of the outer white tissue region ("rind"), and others.

Subjectively, a watermelon is ripe when the inner edible tissue is sweet to the taste and the tissue's texture has not significantly degraded. Texture degradation occurs when the tissue around the seed cavities becomes very soft and the tissue has a gritty feel when eaten.

Frequency response testing methods have been applied to fruits and vegetables in many ways, but most commonly involve either impulse testing or the use of a vibrating plate. This review highlights some of the research using both methods.

Clark (1975) found high correlation between decay time of sound waves crossing a watermelon and firmness of the watermelon tissue. Yamamoto et al. (1980) found high correlation between natural frequencies and watermelon maturity judged by the researchers. In both studies, watermelons were excited using an impact force, and a microphone was used to measure the emitted sound pressure from the opposite side of the melons. Armstrong, Zapp, and Brown (1989) applied much the same technique to apples. They found good correlation between core modulus of elasticity and natural frequencies.

Mizrach et al. (1989) and Mizrach et al. (1988) used ultrasonic methods on core samples of winter melons and other fruit samples. High correlation between the depth of the sample and the attenuation coefficient was found for the winter melons, while poor correlation was found with wave propagation velocity.

Natural frequency of a specimen is affected by the mass of the specimen. Several correction factors have been proposed by other researchers. The correction factor mf^2 was used by Abbot et al. (1968) and Finney (1971, 1972). The correction factor, $m^{2/3}d^{1/3}f^2$, was used by Cook (1972). (For both correction factors, m refers to mass, f to frequency, and d to density). Performance of the correction factors varied. Yamamoto et al. (1980) tried both correction factors on natural frequencies and found that the corrected frequency data had insignificant correlation values ($r<0.5$) with the maturity parameters. An explanation for the low correlations was not given, but I speculate that low correlations were due to high correlation between mass and maturity.

Several researchers have studied use of a vibrating plate apparatus to measure frequency response of fruit tissue. Mahan and Delwiche (1989) created a model of a vibrating plate for the determination of firmness of peaches. Peleg et al. (1989) found good correlation between firmness of avocado fruit and resonant frequency values. They used a vibration table and swept through a predetermined frequency band to obtain the frequency response of the fruit.

De Baerdemaker et al. (1982) studied the use of sonic spectrum analysis as a means of sorting fruit, specifically apples. They would drop the fruit a short distance onto a piezoelectric force transducer and use a Fast Fourier Transform to attain the spectrum. They found good correlation between Magness-Taylor test and the magnitude at specific frequencies. Dropping the fruit a short distance creates a mechanical impulse, hence impulse testing to attain the spectrum.

Delwiche et al. (1987) used the dropping technique on peaches to determine maturity. They used the magnitude of short frequency bands centered at 250 Hz, 272 Hz, 295 Hz, and 318 Hz as a measure of tissue firmness. Magnitude at the individual frequencies was obtained by passing the signal from the transducer through a band pass filter, rather than calculating the frequency spectrum of the signal. Results of the study showed strong correlation between firmness of the peaches and the energy content at the higher frequencies. Perhaps the most interesting observation was that mass was poorly correlated with energy content of the higher frequencies.

CHAPTER III

EQUIPMENT AND MEASUREMENTS

Introduction

This chapter contains a description of the impulse testing system used to measure impulse frequency response of watermelons. The entire system consisted of a Personal Computer, a 24-volt power supply, a digital oscilloscope, a low-pass filter, and a sensor unit which contained an impulse generator and vibration transducer. Figure 1 shows a schematic of the equipment and prototype sensor used during the summer of 1990. The Personal Computer, 24-volt power supply, and digital oscilloscope are all "off the shelf" units. The low-pass filter was specially constructed for this work and is a 4th-order active analog filter with a corner frequency of 1500 Hz. The sensor unit consists of a piezoelectric transducer that converts vibrations into a measurable voltage, and a solenoid that excites the watermelon with a mechanical impulse.

The impulse testing system is keyboard-controlled in the following manner. Power to the solenoid is controlled by a solid-state relay that is connected to the parallel port of the computer. When the control program in the computer sends high logic to the parallel port, the solenoid is activated and generates an impulse. Voltage across the piezoelectric transducer created by the vibration of the melon is passed through the low-pass filter and then measured by the digital oscilloscope. The oscilloscope is connected to the computer by an IEEE488 interface adapter board.

After the oscilloscope records the data, they are transferred to the computer and stored for later processing.

The remainder of this chapter contains descriptions of the components used in the system. I present the design procedure for the impulse frequency response sensor and low-pass filter. For the "off-the-shelf units", I give only a brief description of each.

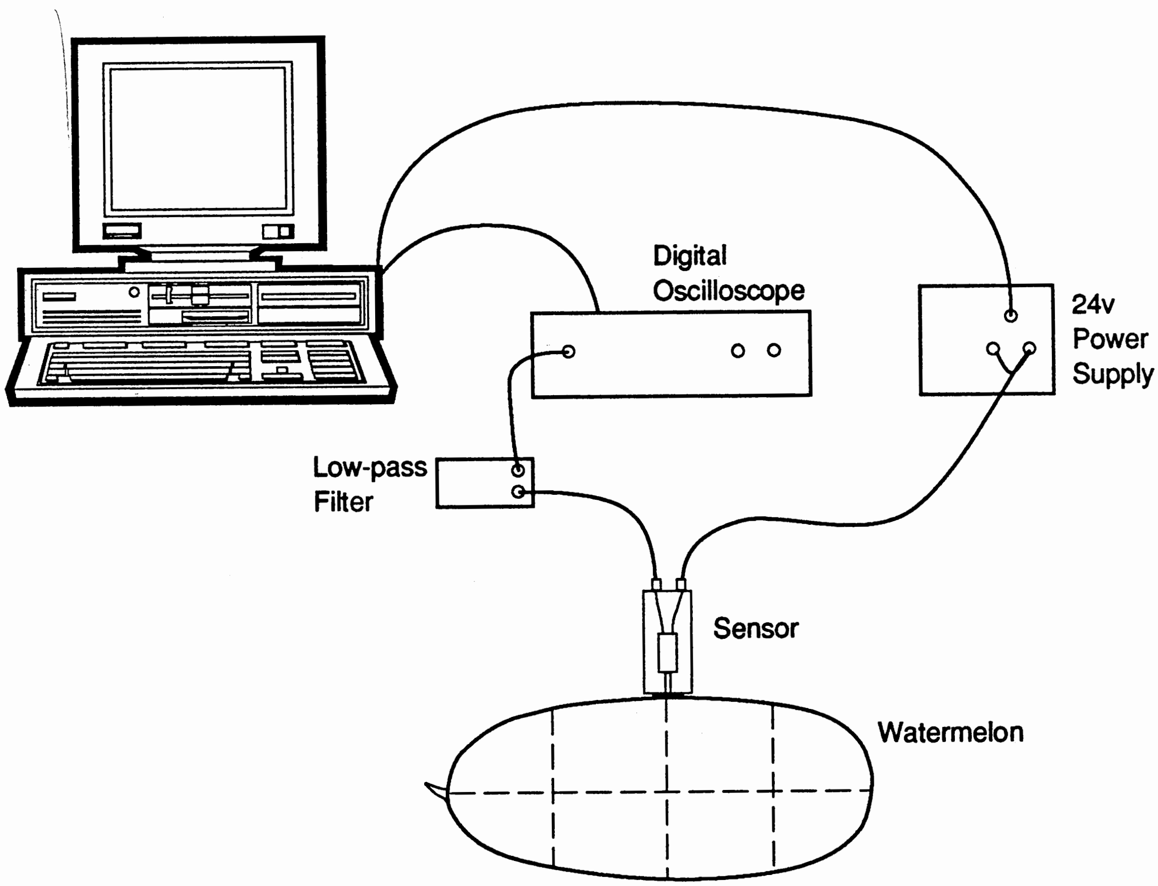

Figure 1. Diagram of impulse frequency response system

Personal Computer

An Intel 386 based IBM clone was used to control the system during testing, and to process the data. I wrote the data acquisition program and signal processing programs used to analyze the data. The interface adapter used for transferring data from the oscilloscope to the computer was a MBC-488 manufactured by Metrabyte Corporation and included interface software.

Digital Oscilloscope

The digital oscilloscope was an R1288 manufactured by Rapid Systems. This oscilloscope can sample two channels of analog signals at frequencies up to 1 MHz with an amplitude resolution of ± 2048 divisions. An IEEE488 interface is built into the oscilloscope. The R1288 digital oscilloscope has an input impedance of 2 Mohms.

Power Supply

A 24-volt power supply equipped with a solid-state relay was used to power the solenoid which excited the melons. The solid-state relay was closed with a high logic signal obtained from the parallel port of the computer. Length of the high logic signal was controlled with the data acquisition program. For our test, the duration of the signal was 0.01 seconds.

Sensor Unit

Criteria for choosing a vibration transducer were sensitivity and frequency band width. Criteria for choosing the excitation source were energy input requirement and frequency bandwidth of the energy input. The preliminary design criteria are listed below:

1. Frequency bandwidth of the sensor, 0 to 1000 Hz
2. Signal-to-Noise ratio, > 50
3. Natural frequency of supporting apparatus, > 1000 Hz
4. Sensor and excitation source be contained in one hand-held unit.

Frequency bandwidth requirement for the sensor was set, based on the literature review and then checked by impulse testing sample melons. Yamamoto et al. (1980) found natural frequencies of watermelons to lie in the band from 80 to 500 Hz. Preliminary testing revealed the sample signals did not to contain any significant frequencies above 500 Hz. Tests were not performed to verify that the absence of signals at higher frequencies could be partly attributed to the sensitivity of the piezoelectric transducer. However, the piezoelectric transducer was sensitive to the resonant frequencies of the plexiglass housing which occurred above 2500 Hz. Preliminary tests were performed with a sampling rate of 10 kHz.

The signal-to-noise ratio requirement was set at 50. A 2 percent noise was expected to be small compared to varietal and melon-to-melon variations. Natural frequency of the sensor housing structure was constrained by design to well above 1000 Hz. Since the frequency band of interest was from 0 to 500 Hz, interference above this range could be removed with a low-pass filter before sampling, eliminating aliasing errors.

Piezoelectric Transducer

The transducer selected to measure the signal was a piezoelectric tone transducer manufactured by NGK Spark Plug Company. This transducer has its lowest resonant frequency at 7 kHz. The charge across the transducer was measured directly as voltage with the high impedance digital oscilloscope.

For this transducer, the attenuation difference caused by frequency dependence can be shown to be negligible for 0 to 500 Hz. The damping constant approaches zero for a piezoelectric transducer (Nuebert 1975). Thus, the output dependence on frequency can be written as,

$$\frac{V}{Vo} = \frac{1}{1-(f\,/\,fr)^2} \tag{1}$$

where:

V = Output voltage at frequency, f
Vo = Output voltage at frequency, 0
f = Frequency of interest
fr = Lowest resonant frequency, 7kHz

Using Equation (1), the percentage of error in the output of the transducer at 500 Hz is approximately 0.5 percent.

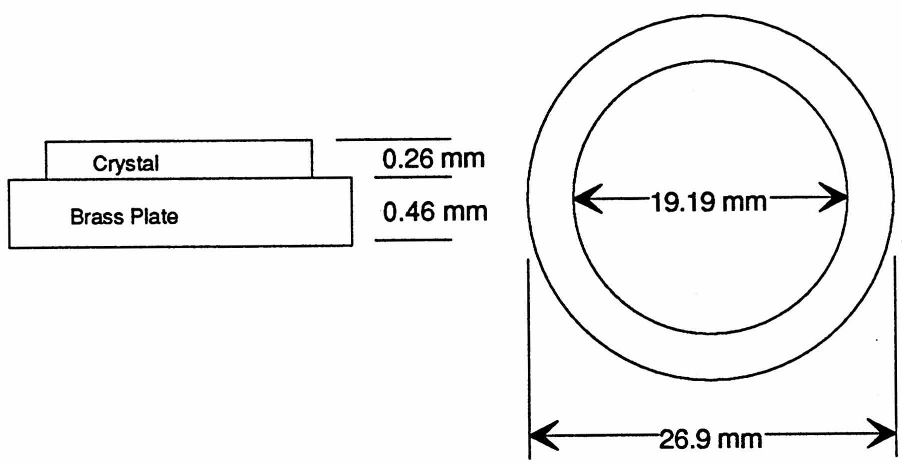

Figure 2. Diagram of piezoelectric transducer

Impulse Generator

Impulse testing was chosen because of speed and simplicity in acquiring the frequency spectrum of the specimen. A frequency spectrum can be obtained through impulse testing by applying a short duration pulse (either by impact or acoustically) and then measuring the resulting vibrations. The response signal can then be transformed from the time domain to the frequency domain to obtain the spectrum.

For impulse testing, the excitation source must create a short duration pulse which can be done mechanically by striking the object directly, or sonically by transmitting energy to the object through sound pressure. The time duration of an ideal impulse is zero. In practice, an impulse has a short time duration, and the quality of the impulse generator is measured by the duration and peak of the pulse. The spectrum of an impulse has a constant value for all frequencies. Hence, an excitation through an impulse is an excitation with all frequencies of the spectrum.

Both mechanical and sonic impulse methods were explored. The primary limitation was due to low energy input into the watermelons. In the design criteria, restriction on signal-to-noise ratio was set at 50. To increase the ratio, either noise had to be reduced, or signal increased, or both. Noise levels measured were on the order of 1 micro volt. This level was assumed to be a reasonable minimum limit. To meet the 50:1 ratio, response signals should exceed 50 micro volts.

Three devices were tested for producing an impulse; the piezoelectric transducer, a small speaker, and a small solenoid. Impulse tests were performed on winter melons using each of the three devices to determine signal-to-noise ratios. Signal-to-noise ratios for the winter melons were expected to be similar to the noise ratios of watermelons. The reasoning was that tissue properties of the winter melons are similar to those of watermelons. In practice, the winter melons signal-to-noise ratio was larger due to higher energy vibrations in the winter melons. The higher energy vibration may be attributed to size. Because of the smaller size, the ratio of "rind" to inner tissue of the winter melons was larger. The firmer outer "rind" requires less energy to stimulate vibration, thus the larger ratio results in larger amplitude of vibration.

The most desirable sensor configuration is to use the transducer as both the receiver and sender. Although the piezoelectric transducer has been determined to be adequately sensitive to impulse response signals, it was inefficient in producing an excitation pulse. Maximum excitation with the transducer was limited by arcing and heat generation. At the maximum levels used for testing, the transducer became too hot to touch after 0.1 second of excitation. Any more voltage input caused arcing across the transducer. At this transmission level, the signal-to-noise ratio for a small winter melon was approximately 2. The ratio is well below the needed minimum, making the transducer an unacceptable impulse source.

Exciting the watermelon acoustically with a small speaker is appealing, because the speaker would not have to be in physical contact with the watermelon. The small speaker tested was 2.5 inches in diameter and had an energy impulse sufficient to meet the signal-to-noise ratio criterion of approximately 75. Impulse from the speaker was of extremely short duration and qualitatively the impulse sounds like a loud click. Sound pressure was on the order of 100 db. Operator safety measures would have to be taken to reduce exposure to the high sound pressures.

The solenoid was found to have the highest signal-to-noise ratio of the devices tested on the winter melon. Average signal-to-noise ratio was calculated to be approximately 300, with the maximum amplitude from the transducer greater than 1 volt. This test was done with the piezoelectric transducer taped to the melon surface, and with the solenoid being held so that the plunger struck the melon's surface. The solenoid plunger did not create enough force to cause visible damage to the winter melon. Quantitatively, the force is about the same as a firm thump with a finger.

The solenoid was chosen for the excitation source because of favorable performance in the test. Both the speaker and the solenoid delivered sufficient energy, but the speaker caused more operator safety problems. Also, the solenoid being smaller in size, would be easier to mount into a single unit with the transducer.

The solenoid and transducer can be mounted as one unit. The design issue, insuring minimum interference from the acceleration and de-acceleration of the solenoid plunger, remained. Natural frequency of the de-accelerating plunger is between 15 and 20 Hz.

Prototype Structure

Two mounting configurations of the transducer and solenoid were tested. The first configuration had the solenoid mounted to one side of the transducer. The solenoid plunger, when activated, would strike the watermelon's surface giving a maximum excitation energy. The problem with "side-by-side" mounting is that both the transducer and solenoid plunger must be in contact with the watermelon surface, creating two centers of contact. Assuring ideal contact of both centers on the irregular surface of a watermelon is difficult and uncertain. Imperfect contact of the transducer and plunger results in non-uniform energy input and variable transfer characteristics between the watermelon and transducer.

The second configuration, alleviates the problem of two centers of contact by mounting the transducer on an acrylic base directly beneath the plunger. When the solenoid is activated, the plunger strikes the back of the transducer transferring the impulse energy though the transducer into the watermelon. Less energy is transferred to the watermelon because of absorption in the transducer and acrylic layer, but only one contact point is required. The transfer characteristics between the watermelon surface and the transducer were more consistent with one contact point. For the watermelons tested, at least half of the surface area of the transducer was in contact with the watermelon surface.

Another benefit of the plunger striking the back of the transducer is that a measure of the input energy can be obtained from the peak of the impulse. This peak amplitude cannot be used to determine the absolute amount of energy transferred to the watermelon because the contact between the watermelon and transducer is imperfect. However, a relative comparison of the input energy to response energy can be measured from this peak. Amplitude of the impulse can be used to check the function of the solenoid and crystal during testing to ensure that the system is not drifting or that the crystal has not been damaged.

Prototype Sensor

Figure 3 shows a schematic drawing of the prototype sensor. Figure 10 presents the design drawings of the sensor. The body of the sensor unit is made of clear acrylic plastic (Plexiglass). Power for the solenoid is supplied at the top of the unit with a shielded cable. The piezoelectric transducer is connected to the oscilloscope through the top of the sensor by coaxial cable (type RG58cu).

The solenoid was activated with a 24-volt power supply. Solenoid specifications are given in Appendix A. A small spring returned the solenoid plunger after activation. A foam pad glued to the top of the plunger served as a damper. The natural frequency of the spring and damper varied between 15 and 20 Hz and remained constant through out the test.

Natural frequencies of the sensor body were approximately 2500 Hz and 4500 Hz. These natural frequencies were measured by activating the solenoid while suspending the unit by the power cord. Output of the crystal was then measured by the oscilloscope, with a sampling frequency of 100 kHz. A low-pass filter was not used in this test, therefore the possibility of frequencies produced by alias signals is present. However, all significant resonance frequencies were above 2500 Hz. Therefore, the source of the resonances is not important, because frequencies above 2500 Hz will be removed by the low-pass filter.

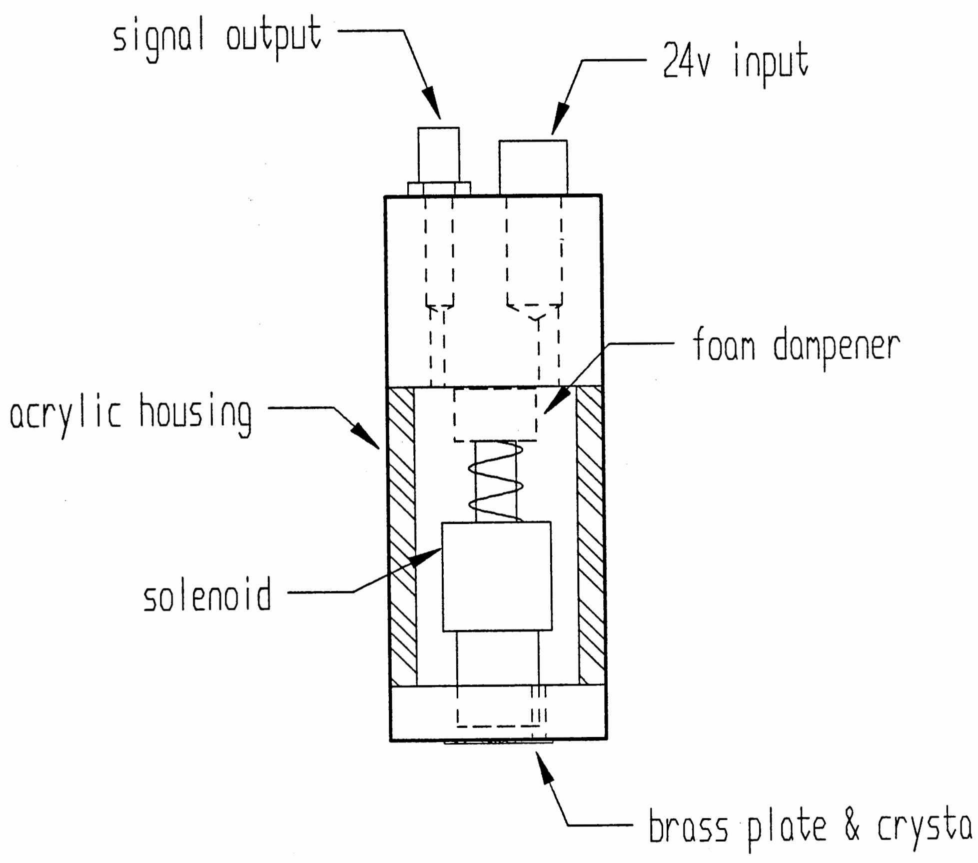

Figure 3. Diagram of impulse frequency response sensor

Energy Output of Solenoid (Pendulum Test)

A pendulum made from a light nylon cord and a steel ball bearing was used to measure the energy output of the solenoid at the surface of the piezoelectric transducer. Figure 4 illustrates the configuration of the pendulum test.

At rest, the pendulum was situated so that it contacted the piezoelectric crystal without being displaced from vertical. When the solenoid was activated, the impulse force was transferred to the pendulum, causing the pendulum to swing to the right. The amount of energy transferred to the pendulum was approximately equal to the change in total energy of the pendulum from rest position to the maximum displacement to the right. If energy losses to air friction and sound generation are neglected, the change in total energy is equal to change in gravitational potential energy of the pendulum ball. Change in potential energy can be written as:

$$E = mg(h_{right} - h_{rest}). \tag{2}$$

where:

h_{rest} = Height of pendulum at rest
h_{right} = Height at farthest displacement
m = Mass of pendulum
g = Acceleration of gravity

$$(h_{right} - h_{rest}) = 0.5(L2 - X2) - L \tag{3}$$

where:

X = Linear distance of travel from point of rest to maximum displacement distance
L = Length of pendulum

To measure the energy change of the pendulum, the response of the transducer when the pendulum struck the transducer on the return swing was used. Again, assuming negligible energy loss from air resistance, response of the transducer to the pendulum striking it will be directly proportional to displacement of the pendulum.

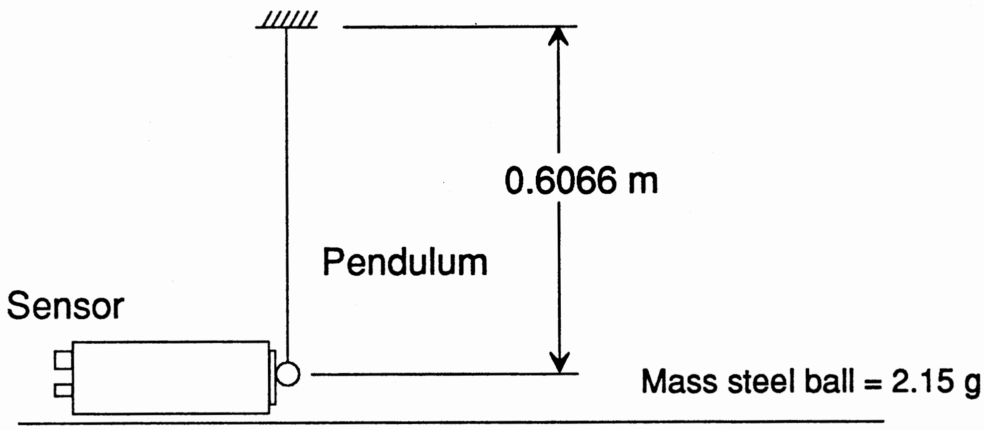

Figure 4. Pendulum configuration used to calculate energy transferred by solenoid

Voltage response of the transducer to displacement of the pendulum was calibrated by placing a fence a known distance from the face of the transducer. The steel pendulum was held against the fence by a magnet positioned on the backside of the fence. By quickly moving the magnet, the pendulum was released uniformly. Voltage response of the transducer was recorded for several different distances. Table 20 contains the calibration data for peak voltage to displacement.

Equation (4) relates potential energy of the pendulum found from Equation (2) and (3) to voltage of the crystal. Equation (4) was found by linear regression and has an r^2 of 0.90.

$$E = 0.0001993(PV) + 0.0003964 \tag{4}$$

where:

E = Energy in Joules
PV = Peak voltage response of crystal

Average energy calculated using Equation (4) for 20 repetitions was 0.0007 Joules. This value is for the sensor unit oriented horizontally. When actually testing the watermelons, the sensor was held vertically. Thus, the force of gravity contributed to the impact energy. To compensate for the contribution of gravity, the transducer was once again used to find the relative difference between the energy of the solenoid depending, on orientation.

Difference in peak voltage of the transducer for vertical and horizontal orientation was found to be 1.994 volts. Entering 1.994 V into Equation (4), the energy difference between the two orientations becomes 0.0008 Joules.

Estimated energy transfer from the sensor to the watermelon is less than 0.0015 Joules, when transmission losses are considered. This is a very low amount of energy, but the transfer time of this energy was estimated to be less than 0.01 seconds.

Low-Pass Filter

The frequency band of interest is from 0 to 500 Hz. Therefore, a low-pass filter can be placed between the transducer and oscilloscope to remove frequencies higher than 500 Hz. Nyquist criterion states that to eliminate aliasing in a sampled signal, the signal must be sampled with at least at twice the frequency of the highest frequency appearing in the signal.

To reduce aliasing in the sampled signal, the low-pass filter design in Appendix B was used. Figure 11 shows percent of signal passing for several frequencies. The filter is a 4th-order active low-pass filter with a corner frequency at 1500 Hz.

A sampling rate of 5 kHz was used with this filter in the system. Thus, according to Nyquist criterion, the highest frequency detected is 2500 Hz. At 500 Hz 80 percent of the signal was passed. Only 20 percent of the signal was passed at 2500 Hz.

The filter also served as an amplifier with gain of 3.3. The amplifying function was part of the first stage of the filter. By increasing the signal, contribution of noise by the filter in the latter stages was reduced to an acceptable level.

CHAPTER IV

METHODS AND PROCEDURES

Introduction

This chapter presents the experiment used to test the impulse frequency response sensor. The experiment was planned to allow measurement of the effects of watermelon maturity as well as mass on calculated spectrum parameters. Watermelons used in the study were grouped according to size and maturity with five watermelons falling into each group. The basic problem with grouping the melons is that accurate, non-destructive methods do not exist to allow determination of maturity.

The final part of this chapter describes procedures used to obtain and process the data. Physical measurements and equipment used to make the measurements are described.

Experiment Layout

The objective of this experiment was to find a parameter from the impulse frequency response sensor which was correlated to watermelon maturity. From the literature, it was found that frequency content of a watermelon spectrum is affected by material properties as well as mass. During the maturing stage, both material properties and mass of a watermelon change. Therefore, the experiment was designed in a way to allow analysis of different maturity stages, independent of mass.

To separate stages of maturity from mass, watermelons close to the same mass, but at different maturity levels were selected. Likewise, to determine the effect of mass on the impulse frequency response, watermelons of the same maturity level, but of different masses, were selected. Table 1 shows the size and maturity groupings for the experiment layout. The design was not constructed to measure the effects of interaction between maturity and mass.

In the experiment layout, size classification depended on diameter of a watermelon along the major and minor axes. All watermelons in a size classification were to be picked with their major and minor axes dimensioned within ± 1/2 inch of the respective mean diameter. By restricting the size, the effect of geometry and mass on the spectrum was reduced.

TABLE 1

WATERMELON GROUPING FOR EXPERIMENT LAYOUT

	Size Classification		
Maturity	Small	Medium	Large
10 "days-till-ripe"	0	5	0
5 "days-till-ripe"	0	5	0
3 "days-till-ripe"	0	5	0
Mature	5	5	5
Over ripe	0	5	0

Within a size classification, watermelons were to be grouped into tentative maturity levels, as judged by the picker. Four maturity levels were to be selected for the middle size classification (5 watermelons at each maturity level). Maturity levels were set at 10 "days-till-ripe", 5 "days-till-ripe", 3 "days-till-ripe", and mature. Small and large size classification will contain 5 watermelons each with all watermelons being ripe.

Tentative maturity classifications were arranged as shown in Table 1 to aid in selecting enough watermelons to meet the experiment layout. We did not use this maturity rating in our analysis. Once watermelons were tested, the maturity grouping was based on destructive measurements.

Table 2 presents the distribution of watermelons used in the summer 1990 study. These watermelons are of the Allsweet cultivar and were picked from an irrigated field near Hydro, Oklahoma. Watermelons were picked over a 4-week period in groups of less than 20 per week. As expected with a growing crop, most of the immature watermelons were picked during the first two weeks, and most of the mature watermelons were picked during the last two weeks.

TABLE 2

WATERMELON GROUPING FOR THE SUMMER 1990 MATURITY STUDY

	Size Classification			
Refraction	<8 kg	8-10 kg	10-12 kg	>12 kg
6-7	0	2	0	0
7-8	2	4	2	0
8-9	1	4	1	0
9-10	1	11	1	3
10-12	2	11	2	14
>12	0	0	3	1
Total	6	32	9	18

Size and maturity distribution of watermelons in the experiment was not as uniform as desired, but was considered acceptable. Notice in Table 2 that there are a disproportionate number of 8 to 10 kg watermelons as well as a disproportionate number of 9 to 12 Rdiv (Rdiv stands for divisions on the refractometer scale) watermelons. The main problem in meeting the experiment layout as designed was determination of maturity during picking. An educated guess of the maturity stage of each watermelon was made on outward appearance, but subjective determination of watermelon maturity is imprecise. To try and complete the experiment layout, 74 watermelons were picked when the original design called for 35 watermelons.

In comparing Table 1 with Table 2, you will notice I changed the maturity category from "days-till-ripe" to refraction. Optical refraction of the juice of the melons was used as a crude measure of sugar content. Refraction numbers did not correspond with specific groups of "days-till-ripe", but did appear to be the best parameter for dividing the watermelons into maturity categories. Comparing subjective taste comments on maturity and refraction, I determined that for this variety and field, a watermelon had reached maturity at a refraction > 10 Rdiv. Watermelons with a refraction of 9 Rdiv to 10 Rdiv were considered to be slightly immature, possibly 2 to 3 days from peak maturity. Refraction is directly proportional to maturity, although a clear-cut line between the ripe and immature watermelons does not exist. However, a relative maturity grouping for determining if the experiment contains a proportionate blend of immature and mature watermelons is possible.

The problem with using refraction as a measure of maturity is that groupings between mature and immature overlap. For our test, some watermelons with a refraction of less than 10 Rdiv were judged to be mature while some with greater than 10 Rdiv were judged as immature. Because of this overlap, a combination of refraction and one or more other tissue properties may help to predict relative maturity more accurately. In Chapter V, multiple regression techniques were used to combine destructively measured parameters.

Also note that these refraction numbers are specific to this cultivar, for this particular field, for the summer of 1990. Refraction for one cultivar changes from region-to-region, year-to-year and even field-to-field; depending on temperature, available moisture, and condition of the leaf canopy (Patterson 1990).

Testing

In the summer of 1990 experiment, all watermelons were tested in the same manner. A list of parameters is listed below in order measured:

1. Length along both major and minor axes
2. Weight
3. Impulse frequency response
4. Optical refraction of watermelon tissue
5. Firmness of the watermelon tissue using hand-held penetrometer
6. Outer white tissue thickness, "rind" thickness
7. Modulus of Firmness measurements.

Measurements 1 and 2 are non-destructive physical measurements of watermelons. Measurement 3 is the non-destructive impulse frequency response. Measurements 4-6 are destructive physical measurements of the inner tissue of watermelons and were taken on representative cross-sections of the watermelons.

Testing of watermelons was conducted in the following manner. Fifteen to twenty watermelons were picked and stored overnight at approximately 75°F. Outside dimensions, weight, and acoustical information were taken first. Second, the watermelons were cut parallel with the minor axis, and physical measurements of the tissue were recorded. A subjective rating of maturity based on taste and texture was also recorded. This rating was used as a reference in selecting destructively measured tissue parameters for best prediction of relative maturity.

Refraction and penetrometer measurements were taken at the same locations on two representative cross-sections of each watermelon. Each cross-section was divided into four regions; Rind-tissue, Tissue 1, Tissue 2, and Heart. Figure 5 illustrates how each cross-section was divided and sampled. On each cross-section, two measurements were taken in each region.

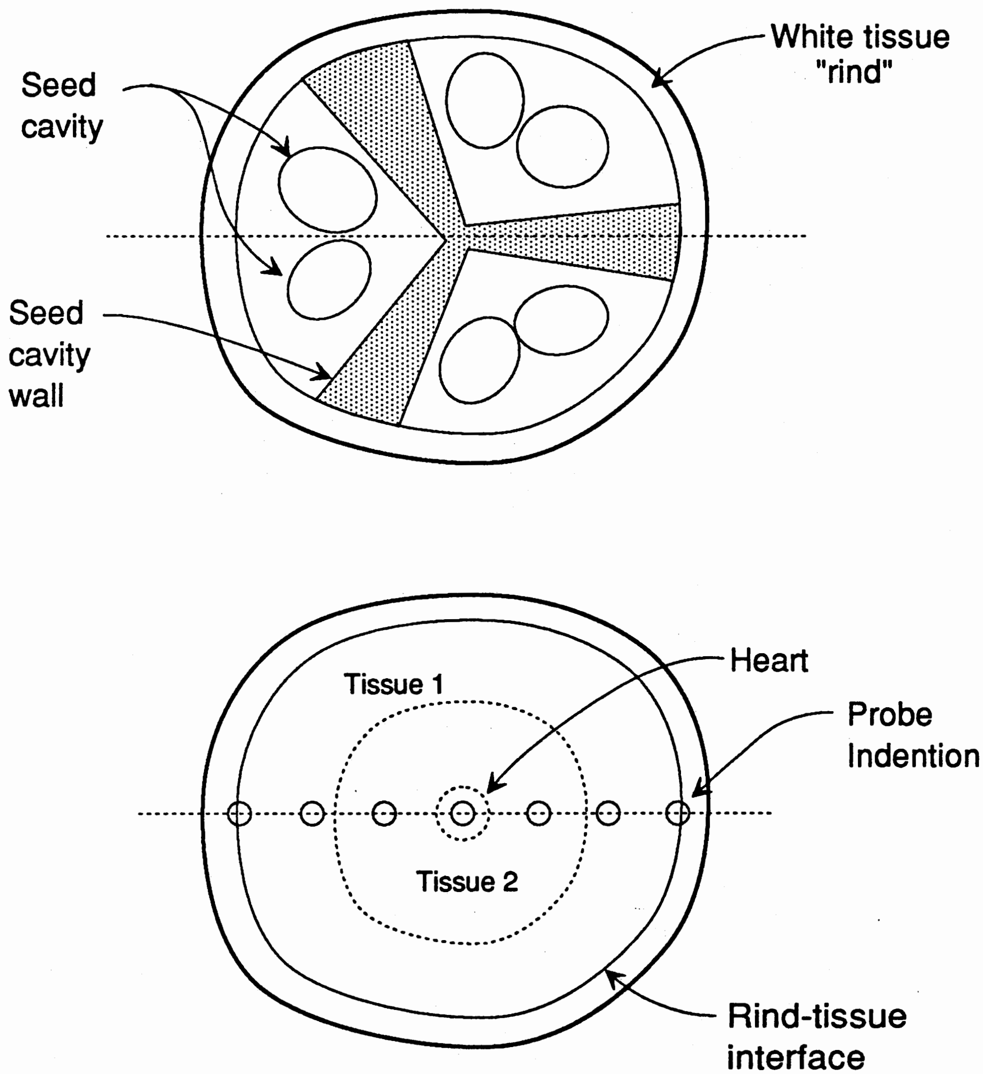

Figure 5. Cross-section of a watermelon

The cross-section of a typical watermelon has three seed cavities that are divided by seed cavity walls. Seed cavities have a higher refraction and softer tissue structure than the dividing walls. When sampling a cross-section, one set of penetrometer and refraction measurements was taken through a seed cavity, and one set of measurements was taken along a seed cavity wall. Penetrometer measurements were taken first, and then refraction measurements were taken using the juice left in the indentation made by the penetrometer probe. Four samples of each region were averaged together to create the data found in Table 22.

Diameters and Weight

Major and minor diameters were measured along one representative cross-section of each watermelon. The dimensional measurements were to be used in the field to aid in selecting watermelons of desired size. Weight of the watermelons was taken in the laboratory. The final size groupings were based upon these weights.

Firmness

A McCormick Fruit Pressure Tester (Model FT 327) was used to determine firmness of the tissue. The McCormick penetrometer is equipped with two diameters of cylindrical probes; a large probe with diameter of 11 mm, and a small probe with diameter of 8 mm. The 11 mm probe was used for testing the four regions of each cross-section.

Outer white tissue, sometimes called the "rind" of the watermelon was too firm to measure with the 11 mm or 8 mm probe. A smaller diameter probe would decrease the force required and would allow the penetrometer to be used for firmness of the outer white tissue. For our test, the peak force from the Modulus of Firmness measurements was used as the firmness measurement for the outer white tissue.

Refraction

Refraction of the watermelon tissue was measured by a Fisher Hand Held Refractometer (Model 13 946 60A, 0-32 percent). The refractometer measures refraction in percent sugar content. The refractometer is calibrated for pure sucrose solutions. The refractometer was not specifically calibrated for watermelon juice which will contain varied amounts of salts, pigments, sugars, minerals, and other components that affect optical refraction. With this in mind, the optical refraction measurements were not taken to mean the literal amount of sugar concentration, but rather the relative amount of sugar concentration as well as other components that affected refraction. Therefore, the refractometer readings are presented in scale divisions (Rdiv) with each division equivalent to 1 percent sucrose concentration.

Refraction increased as watermelons reached peak maturity. It is also known, although not well documented, that the largest portions of sugars are transferred into a watermelon during the last 7 to 10 days of maturity (Patterson 1990). Other soluble substances, such as salts, also have a large transfer rate during this period, making refraction a promising parameter for relative maturity. In my study, refraction increased significantly as watermelons reached peak maturity.

Outer White Tissue Thickness

Outer white tissue of a melon is often referred to as the, "rind". In physiological terms, the rind is only the outer green cover which is approximately 1 mm thick. The exact point at which the outer white tissue ends and mature tissue begins is difficult to determine because of the gradual change from immature to mature. This interface does not have a constant thickness and appears to be dependent on the maturity of the watermelon. The white-red tissue line was determined by color. For this test, a consistent shade of pink was selected.

From my observations, outer white tissue thickness of a watermelon appears to decrease rather rapidly during early stages of watermelon maturity (approximately 14 to 7 "days-till-ripe"). In the latter stages of maturing, however, the rate of decrease in the outer white tissue thickness lessens. Texture of this region continues to change as does the texture of the entire watermelon. Outer white tissue changes from a firm crisp texture to a less-firm strength at peak maturity. As the melon begins to over-mature, the elasticity of the outer white tissue increases. Qualitatively, the outer tissue becomes tough and rubbery in texture.

Change in outer white tissue thickness is not well documented and is difficult to measure, because of the subjectivity involved in determining a line where outer white tissue ends and inner red tissue begins. The interface between the two regions is approximately 10 percent as thick as the outer white tissue. Another problem with using the outer white tissue as a measure of maturity, is that the white tissue portion does not decrease uniformly along the entire circumference of the watermelon. The white tissue region is usually much thinner on the top side of a watermelon than on the underside.

Because of these problems, outer white tissue thickness was judged not to be a good predictor of maturity for our study. Instead of thickness of this region, the textural changes appeared to be more affected by maturing. Slope of the penetration-force versus penetration-depth (Modulus of Firmness) is a measure of textural change and is discussed in the following section.

Modulus of Firmness

An Instron machine (Model TM) mounted with a cylindrically shaped probe was used to measure the penetration-force versus penetration-depth. Probes used had the same shape and diameters as the probes for the hand held McCormick

Penetrometer. Figure 6 shows a sample curve of the penetration-force versus penetration-depth. The slope of the linear region of the curve is referred to as the Modulus of Firmness.

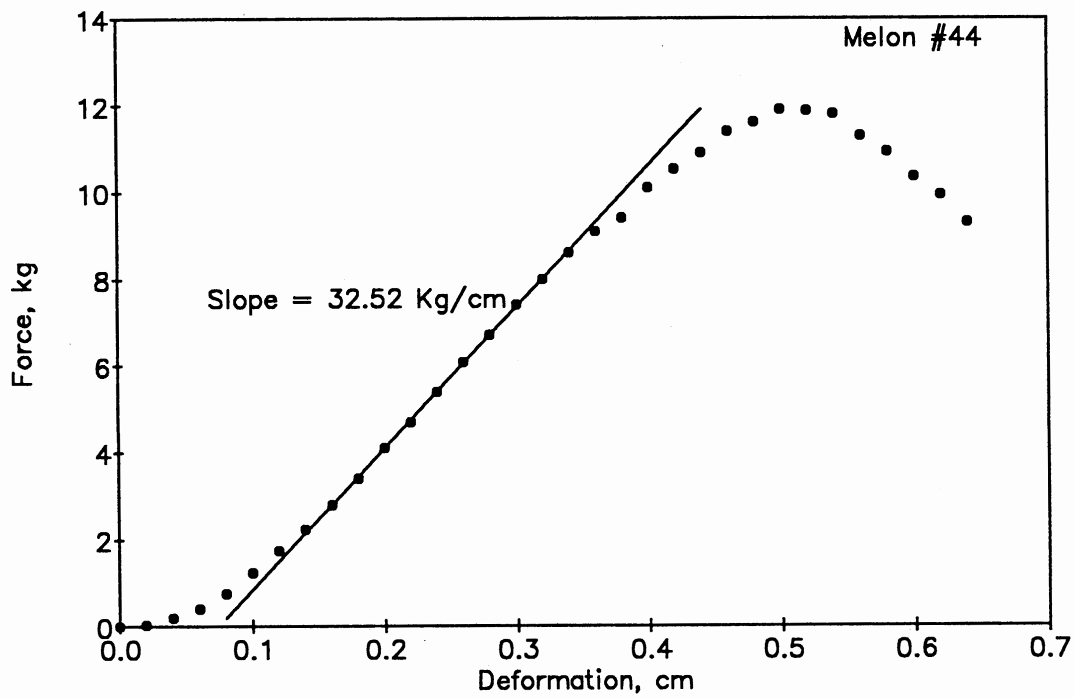

Figure 6. Typical penetration force versus penetration depth curve

Recall that on a stress-strain curve the linear region is referred to as the elastic region, and the slope of this region is called Young's Modulus. Modulus of Firmness is similar to Young's Modulus, however, Modulus of Firmness measurements are taken on in situ sample. Stress-strain curves were not measured because they would require the removal of tissue samples of known area. Removing small samples of watermelon tissue will cause a structural change in the tissue due to loss of moisture. Therefore, measurements on intact samples were preferred over measurements on removed tissue cores.

Modulus of Firmness was measured by pushing the probe at a known rate into a sample cross-section until the peak force was reached. Measurements were taken at three distances from the rind; 8 mm, 20 mm, and 40 mm. At least three measurements at each distance were taken. The average of the measurements for each distance is included in Table 22. Modulus of Firmness is abbreviated MF8, MF20, and MF40, for each of the respective distances; 8 mm, 20 mm, and 40 mm.

The 8 mm probe was used for the 8 mm distance. At 8 mm, the probe was in the outer white tissue only. The small probe was used to ensure that the entire surface area of the probe stayed within the white tissue. For 20 mm and 40 mm, the 11 mm probe was used. To obtain a more accurate profile of the watermelon tissue firmness, Modulus of Firmness was calculated for the seed cavities as well as the seed walls.

Destructively Measured Tissue Parameters

The first part of the analysis was to determine what destructive measured parameters of the melon tissue best quantified relative maturity. Rating of the tissue parameters as maturity indices was accomplished in a subjective manner by comparing tissue parameters with the subjective maturity rating. Tissue parameters that appeared to best quantify maturity were; average refraction for inner three regions, average penetrometer reading for the inner three regions, and Modulus of Firmness at 8 mm (MF8).

Average Refraction refers to averaging the refraction for the inner three regions (Tissue 1, Tissue 2, and Heart). Average Firmness refers to averaging the penetrometer readings for the same inner three regions. Average measurements for the three inner regions were used, because averaging served to remove the fluctuation in measurements caused by the nonhomogeneous nature of the melon cross-section.

The Rind-tissue region was omitted from the averaging because of the inconsistent values of both firmness and refraction. The inconsistent values were due to difficulty in obtaining measurements along the interface between white tissue and red tissue. Difference in firmness and refraction between white and red tissue is large. When taking measurements it was difficult to prevent the penetrometer tip from sliding into the softer red tissue. Because of sliding of the penetrometer, Rind-tissue firmness values contained much more experimental error than the other three regions.

Recall that refraction measurements were taken from the melon juice left in the probe indentions. The sliding of the penetrometer caused the proportion of white tissue juice and red tissue juice left in the probe indention to vary. Because of this variation, refraction measurements for the Rind-tissue region were omitted from Average Refraction.

Impulse Frequency Response

For each watermelon, 7 sample impulse frequency response signals were taken. Figure 7 shows the location of the three impulse frequency response test sites. Three samples were taken at site 1, which is the middle of the watermelon where the major and minor axes cross. Two samples were taken at site 2, which is halfway from the middle of the watermelon to the stem end. Two samples were taken at site 3, which is halfway from the middle of the watermelon to the blossom end.

Figure 8 presents a typical impulse frequency response signal recorded with the piezoelectric transducer. The sample signal is made up of three regions. The initial flat region shows the transducer at steady state before the solenoid is activated. When the solenoid is activated, the acceleration of the plunger causes the signal to decrease to a negative voltage. The voltage signal then rises rapidly when the plunger strikes the back of the transducer driving a pulse of energy into the watermelon.

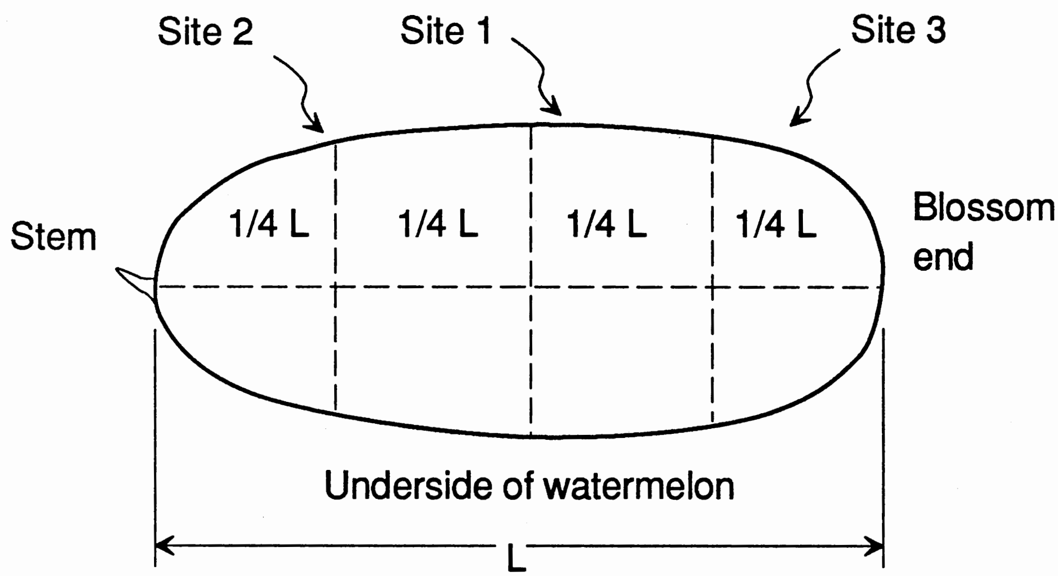

Figure 7. Location of impulse tests

The final part of the signal consists of a combination of the tissue vibration of the watermelon and the de-acceleration of the plunger. De-acceleration of the plunger has a frequency of less than 20 Hz. Energy content of the signal resulting from the de-accelerating plunger is low when compared with the signal from the watermelon. The de-acceleration component was assumed to be constant for all watermelons, and can therefore be regarded as negligible, because all signals were effected in the same way.

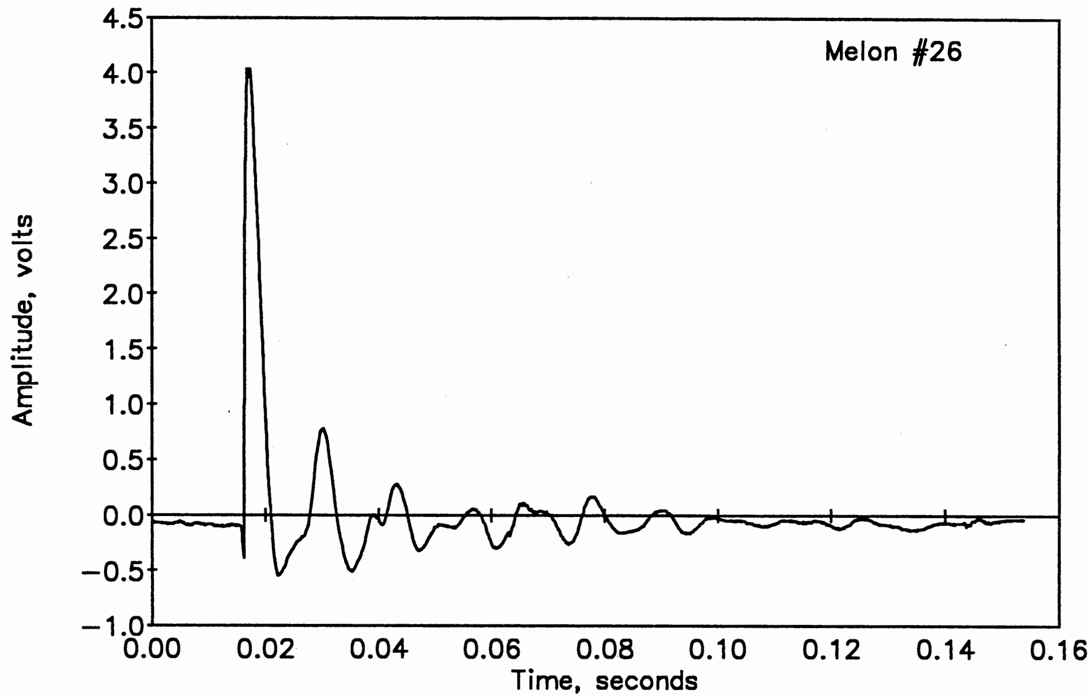

Figure 8. Typical impulse frequency response signal

After studying several impulse frequency response signals from different watermelons, I concluded that only the first 1000 points after the impulse were needed to obtain a complete frequency spectrum of the signal. After the 1000-point mark, attenuation had decreased the signal to the point that noise and quantization error began to degrade the signal. The time frame of 1000 points sampled at 5000 Hz is 0.2 seconds.

Figure 9 presents the frequency spectrum of the signal in Figure 8. The spectrum does not contain the full signal, but shows a windowing of the signal. A 1000-point rectangular window was used with a starting point at the first zero-crossing after the impulse. In equation form, the window can be written as,

$$w(n) = \begin{cases} 1, & zc < n < 1000 + zc \\ 0, & \text{otherwise} \end{cases} \tag{5}$$

where:

zc = first zero-crossing after the impulse

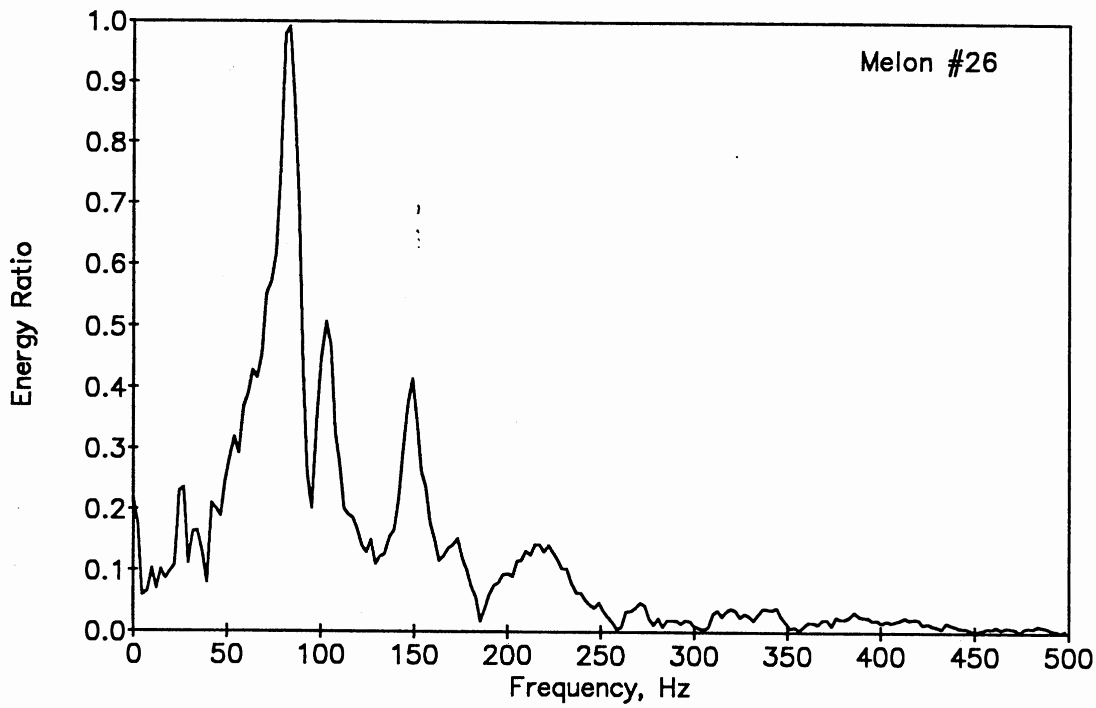

Figure 9. Typical impulse frequency response spectrum

After windowing, the sequence was increased to 2048 points by adding 1048 zeros to the 1000 original points. This procedure allowed the spectrum to be calculated using a 2048 point Fast Fourier Transform. The frequency step of the spectrum can be found by using Equation (6). Entering sampling frequency of 5000 Hz and number of points 2048, the frequency step of the spectrum is 2.441 Hz.

$$\text{Frequency Step} = fs/pt \tag{6}$$

where:

fs = sampling frequency, Hz
pt = number of points in the sequence

During testing of the watermelons, only the first 500 Hz of the signal was considered useful. Therefore, after windowing and taking the Fourier Transform only the first 206 points were stored.

Signal Processing

The impulse frequency response signals were searched for a parameter which was correlated with ripeness by looking at the parameters used by previous researchers. The most common parameter used by other researchers is natural frequency (peak frequency of spectrum). As mentioned in the literature review, natural frequencies are dependent on material properties, shape, density, and mass. A spectrum parameter dependent on material properties but independent on weight was the goal of the spectrum parameter search.

A parameter dependent only on material properties will probably need to be derived from a combination of parameters. Both natural frequency and spectrum energy content are dependent on more than just the material property changes caused by maturing. A combination of the two may make it possible to create a parameter that is solely dependent upon material properties. The reasoning behind the combination of two parameters is that, with two equations and two unknowns, it is possible to solve for the individual components.

Natural Frequency = f(Mass, Material Properties)

Spectrum Energy = f(Mass, Material Properties)

Instead of trying to find two separate parameters and then determine a relationship between the two to predict material change with maturity, I searched the spectrum directly for a parameter that combined energy and frequency location. I tried several different approaches, but had best success with center frequency of the narrowest 50 percent energy band (CFN50) and energy content for the frequency band from 85 to 160 Hz (EB85-160).

Some preliminary processing of the data was performed to combine the multiple impulse frequency response signals for a watermelon into one characteristic spectrum. The combined spectrum is referred to as the average normalized energy spectrum.

Averaged Normalized Energy Spectrum

The averaged normalized energy spectrum was found by normalizing all seven spectra for each watermelon to have a total energy sum of one. These seven spectra were then averaged to create the averaged normalized energy spectrum. This spectrum contains magnitudes only and consists of 206 individual points. The digital frequency step between individual points is 2.441 Hz (5000 Hz/2048). The sum of the magnitudes for all 206 points is equal to one.

Spectra were normalized to one, because the amount of energy input into the watermelons was not constant during the entire test. In order to remove this error, the total energy content for the spectra was normalized. Fluctuation of energy input was caused by inconsistent energy transfer characteristics of the contact between the transducer and the rind. Output energy of the solenoid remained relatively constant during the test period. Proof of this uniformity was the almost constant peak voltage of all signals taken during the study. Since the outside surface of the individual watermelons varied, the surface area of the transducer in contact with the melons also varied, causing a random difference in the amount of energy transferred to the watermelon. This change in surface area contact was assumed to effect only the magnitude of the vibration frequencies and not the characteristic frequencies.

Center Frequency of Narrowest 50 Percent Energy Band (CFN50)

CFN50 is the abbreviation for center frequency of the narrowest 50 percent energy band. CFN50 has units of Hz and is found from the average normalized energy spectrum. For each melon, the average normalized energy spectrum was searched with a computer algorithm to find the narrowest frequency band that contained 50 percent or greater of the total energy of the spectrum. Location of this band is reported by the center frequency of the band. Width of the band was also studied, but correlations <0.5 were found with the destructively measured tissue parameters.

Center frequency of other energy bands including 25 percent, 30 percent, 40 percent, and 60 percent was studied to compare performance to CFN50. Energy bands greater than 60 percent and less than 40 percent showed a significant decrease in correlation with destructively measured tissue parameters. As the energy band dropped, the center frequency approached the peak natural frequency, and correlation with weight increased. As the energy band increased, the center frequency approached a more constant value, because the majority of the energy in the spectra for all watermelons in our test resided between 50 and 250 Hz.

CFN50 is affected not only by peak resonant frequencies, but also by the relative energy content between peak frequencies. Therefore, CFN50 may be thought of as a combination of the different resonant frequencies based on energy distribution in the spectrum.

Energy Content for the Frequency Band from 85 to 160 Hz Band (EB85-160)

EB85-65 is the abbreviation for the energy content for the frequency band from 85.45 Hz to 158.69 Hz. I have rounded the end points of the band to the nearest 5 Hz. EB85-160 was calculated from the average normalized energy spectrum. I wrote a program that searched the entire average normalized energy spectra for a frequency band that had a high correlation of energy content with Average Refraction. For the Allsweet data, this frequency band had end points of 85.45 Hz and 158.69 Hz. In the average normalized energy spectrum, 85.45 Hz corresponds with point 35 and 158.69 Hz corresponds with point 65.

The program started searching at a band width of one, or for a single frequency value. Delwiche et al. (1987) used amplitudes of single frequencies for maturity testing of peaches. However, I did not find a single frequency point which showed significant correlation with the destructively measured tissue parameters.

Use of Sample Correlation

Sample correlation coefficient, r, is used as a statistical means to measure the relation between the spectrum parameters and tissue parameters. A positive correlation means that, when one variable increases, the other variable also increases. Likewise, negative correlation means that, when one variable increases, the other variable decreases. A correlation of one between two variables indicates, that the variables are proportional by a constant.

I considered correlation values > 0.5 significant. The degree of significance is dependent upon the physical meaning of the correlations and how much greater than 0.5 they were.

CHAPTER V

RESULTS AND CONCLUSIONS

Introduction

Presented in this chapter is the correlations of the spectrum parameters, CFN50 and EB85-160, to the destructively measured tissue parameters. Multiple regression was used to combine the tissue parameters into equations that predict the spectrum parameters. Regression statistics are used to show that both CFN50 and EB85-160 are dependent upon the tissue parameters, but are independent upon weight of the melons.

Also presented are the data from an independent test performed on 30 watermelons from a seedless cultivar. This melons were tested in the same manner as the Allsweet cultivar, and the data from this test further support the effectiveness of the spectrum parameters at quantifying maturity levels.

Recommendations for further study are presented. Topics discussed include the subjective maturity ratings, prediction of watermelon quality, and recommendations for building a field unit based on the prototype impulse frequency response sensor. Chapter V ends with a general summary of this thesis.

Spectrum Parameters Correlation with Tissue Parameters

As presented in Chapter IV, the destructively measured tissue parameters were compared to the subjective maturity rating based on taste and texture. Average Refraction was judged to be the best single tissue parameter for quantifying maturity, followed by Average Firmness, and Modulus of Firmness at 8 mm. This comparison was performed by listing the data in Table 22 in ascending order for each of the tissue parameters. If a specific tissue parameter is a good measure of relative maturity then the mature melons will fall on one end of the list and the immature melons will fall on the other end of the list. For simplicity, I will refer to the 30 farthest melons on the mature end of the list as the "mature end"; and likewise, refer to the 30 farthest melons on the immature end of the list as the "immature end". The number of mature melons, according to the subjective maturity rating, found on the "immature end" were counted for each tissue parameter. Likewise, the number of immature melons, according to subjective maturity rating, found on the "mature end" were counted. The tissue parameter with the best relationship to subjective rating would have the lowest number of melons counted. Table 3 shows the results of this test.

TABLE 3

DESTRUCTIVELY MEASURED TISSUE PARAMETERS

Tissue Parameter	Number of immature melons on "mature end"	Number of mature melons on "immature end"
Average Refraction	0	1
Average Firmness	4	3
MF8	7	6

Several parameters from the acoustic signals were calculated and then correlated with the tissue parameters. The two spectrum parameters with the highest correlation values were CFN50 and EB85-160. Other parameters that were tried, but did not have significant correlation with the destructively measured tissue parameters were:

1. Ratio between the second and third highest peaks in the time domain of the impulse response signal. This ratio is related to the attenuation coefficient. Clark (1975) found attenuation to have significant correlation with ripeness determined by color.

2. Relative resonant frequency locations. Shift in predominant frequency location was used by several researchers, and was found to have significant correlation with firmness in apples and peaches.

Table 4 shows correlation values of CFN50 and EB85-160 with the tissue parameters and weight for all Allsweet watermelons tested during the summer 1990. The correlations of CFN50 and EB85-160 with Average Refraction are both significant and positive. Correlations of CFN50 and EB85-160 with MF8 are both significant and positive. CFN50 also has a significant negative correlation to Average Firmness. Negative correlation follows logic if CFN50 is indeed a good predictor of maturity. Watermelon tissue decreases in firmness with maturity, therefore an increase in CFN50 would indicate a decrease in firmness, hence the negative correlation. EB85-160 is poorly correlated to Average Firmness.

TABLE 4

CORRELATION OF SPECTRUM PARAMETERS TO TISSUE PARAMETERS FOR ALLSWEET WATERMELONS

Spectrum Parameters	Avg. Refraction	Avg. Firmness	MF8	Weight
CFN50	0.6745	-0.5104	0.5997	0.5308
EB85-160	0.5645	-0.3491	0.5408	0.4965

Multiple Regression for Allsweet Watermelons

Multiple regression was used to calculate models predicting CFN50 and EB85-160 as functions of the destructively measured tissue parameters. If the spectrum parameters can be modeled as a function of the destructively measured tissue parameters, then I can conclude that the spectrum parameters are indeed a measure of melon maturity. Hypothesis testing using the t test was used to determine if the regression coefficient for each variable was significantly different than zero at the 5 percent level. The t test used was set up in the following manner.

Null Hypothesis, Ho: regression coefficient = 0

Alternative Hypothesis, Ha: regression coefficient is not equal to 0

Reject Ho if $t > t_{(1\text{-confindence level})/2,\, df} = t_{0.9725,\, 73} = 1.980$

Degrees of freedom (df) for Allsweet Data, df = 73
Confidence level = 5%

When the t value of a regression coefficient is less than $t_{(1\text{-confidence level})/2}$ then the variable should be removed from the regression. Note that when two or more t values are less than $t_{(1\text{-confidence level})/2}$, the variable with the lowest t value before performing the next regression is deleted. The minimum confidence level of each t value is included in the regression statistics.

The F test was used to determine the significance of the multiple regressions. For the Allsweet data an F ratio > 2.13 means that the regression equation is significant at the 5 percent level. All multiple regression equations presented had F ratio's > 2.13.

Table 5 contains the regression statistics and equation for CFN50 as a function of Average Refraction and MF8. The t values show that the regression coefficients for both tissue parameters are significantly different than zero at the 5 percent level. The correlation for this equation, 0.734, is the highest correlation between spectrum parameters and tissue parameters for the Allsweet melon data.

Also note that both regression coefficients are positive values. This means that as Average Refraction or MF8 increases that maturity is expected to increase. The positive regression coefficients follow the positive correlations found in Table 3. On the following multiple regressions, only regression coefficients that do not have the same sign as the respective correlation in Table 4 will be pointed out.

TABLE 5

CFN50 AS A FUNCTION OF AVERAGE REFRACTION AND MF8

CFN50 = 2.602(Avg Refraction) + 0.3513(MF8) + 42.76

$r = 0.7342$ $r^2 = 0.5391$ F ratio = 41.524

Variable	Variance	Standard Deviation	t Value	Confidence Level
Avg. Refraction	0.245	0.495	5.257	<0.1
MF8	0.010	0.098	3.599	<0.1

TABLE 6

CFN50 AS A FUNCTION OF AVERAGE REFRACTION, MF8, AND AVERAGE FIRMNESS

CFN50 = 2.041(Avg Refraction) + 0.376(MF8) - 2.693(Avg Firmness) + 51.36

$r = 0.7387$ $r^2 = 0.5456$ F ratio = 28.013

Variable	Variance	Standard Deviation	t Value	Confidence Level
Avg. Refraction	0.561	0.749	2.725	0.8%
MF8	0.010	0.101	3.734	<0.1%
Avg. Firmness	7.274	2.697	-0.998*	167.0%

*Regression coefficient not significantly different than zero

Table 6 presents the regression statistics and equation for CFN50 as a function of Average Refraction, MF8, and Average Firmness. The regression coefficients for Average Refraction and MF8 are again significantly different than zero, but the regression coefficient for Average Firmness is not significantly different than zero at the 5 percent level. Therefore, the addition of Average Firmness to the prediction of CFN50 does not contribute any additional physical information. Hence, the regression equation of Table 5 should be used instead of the equation in Table 6.

Table 7 shows the regression statistics and equation for CFN50 as a function of Average Refraction, MF8, and weight. The regression coefficients for Average Refraction and MF8 are again significantly different than zero at the 5 percent level. The regression coefficient for weight is not significantly different than zero at the 5 percent level. This is an important finding, because this shows that weight does not significantly effect CFN50.

TABLE 7

CFN50 AS A FUNCTION OF AVERAGE REFRACTION, MF8, AND WEIGHT

$$CFN50 = 2.409(\text{Avg Refraction}) + 0.309(MF8) + 0.328(\text{Weight}) + 42.53$$

$r = 0.7386$ $r^2 = 0.5455$ F ratio = 28.011

Variable	Variance	Standard Deviation	t Value	Confidence Level
Avg. Refraction	0.282	0.531	4.533	<0.1%
MF8	0.011	0.106	2.906	0.5%
Weight	0.108	0.329	0.996*	32.2%

*Regression coefficient not significantly different than zero

Table 8 contains the regression statistics and equation of EB85-160 as a function of Average Refraction and MF8. The t values show that both regression coefficients are significantly different than zero at the 5 percent level. The regression equation for Table 8 had the highest correlation for EB85-160 with tissue parameters.

TABLE 8

EB85-160 AS A FUNCTION OF AVERAGE REFRACTION AND MF8

EB85-160 = 0.0214(Avg Refraction) + 0.0037(MF8) + 0.094

$r = 0.6338$ $r^2 = 0.4017$ F ratio = 41.524

Variable	Variance	Standard Deviation	t Value	Confidence Level
Avg. Refraction	0.000	0.006	3.601	<0.1
MF8	0.000	0.001	3.141	<0.1

Table 9 shows the regression statistics and equation for EB85-160 as a function of Average Refraction, MF8, and Average Firmness. The regression coefficients for Average Refraction and MF8 are both significantly different than zero at the 5 percent level. The regression coefficient for Average Firmness is not significantly different than zero at the 5 percent level. Therefore, Average Firmness does not add any additional physical information to the prediction model of EB85-160.

TABLE 9

EB85-160 AS A FUNCTION OF AVERAGE REFRACTION,
MF8, AND AVERAGE FIRMNESS

EB85-160 = 0.0245(Avg Refraction) + 0.0035(MF8) + 0.0151(Avg Firmness) +0.0459

$r = 0.6353$ $r^2 = 0.4036$ F ratio = 15.79

Variable	Variance	Standard Deviation	t Value	Confidence Level
Avg. Refraction	0.000	0.009	2.716	0.8%
MF8	0.000	0.001	2.909	0.2%
Avg. Firmness	0.001	0.033	0.456*	65.0%

*Regression coefficient not significantly different than zero

Table 10 presents the regression statistics for EB85-160 as a function of Average Refraction, MF8, and weight. The regression coefficients for both Average Refraction and MF8 are once again significantly different than zero at the 5 percent level. The regression coefficient for weight is not significantly different than zero at the 5 percent level. Hence, EB85-160 is not significantly dependent upon weight.

TABLE 10

EB85-160 AS A FUNCTION OF AVERAGE REFRACTION, MF8, AND WEIGHT

EB85-160 = 0.0185(Avg Refraction) + 0.0030(MF8) +0.0050(Weight) + 0.091

r = 0.6444 r^2 = 0.4152 F ratio = 16.57

Variable	Variance	Standard Deviation	t Value	Confidence Level
Avg. Refraction	0.000	0.006	2.907	0.4%
MF8	0.000	0.001	2.390	2.0%
Weight	0.000	0.004	1.268*	20.4%

*Regression coefficient with lowest t value not significantly different than zero

Conclusions

The above multiple regressions show that CFN50 and EB85-160 are both significantly dependent upon Average Refraction and MF8, but that both spectrum parameters are not significantly dependent upon weight. The ability to model these two spectrum parameters as a function of Average Refraction and MF8 verifies the spectrum parameters as a measure of ripeness.

Combining destructively measured tissue parameters through multiple regression utilized both refraction and a physical strength property of the melon tissue. Combining a physical strength property with refraction will help to account for mature watermelons with a lower refraction than the average refraction for mature melons. The change in refraction as the melon matures indicates physical changes in the material properties of the melon tissue. However, refraction does not directly measure a physical change such as elasticity or firmness of the tissue, making its correlation with the spectrum parameters indirect. Average Firmness and MF8 are both measures of physical strength properties of melon tissue, and therefore have a direct effect on the spectrum of a watermelon.

Multiple Regression for Seedless Watermelons

The spectrum parameters found in the analysis of the Allsweet cultivar were tested on a seedless cultivar of watermelons to determine applicability to different varieties. During the summer 1990 study, 30 seedless watermelons were picked. Seedless watermelons came from the same field as the Allsweet watermelons and were tested in same way. Table 11 shows the correlation of the spectrum parameters with the destructively measured tissue parameters. Appendix D contains the data for the seedless watermelons, and the complete correlation table for the variables.

TABLE 11

CORRELATION OF SPECTRUM PARAMETERS WITH TISSUE PARAMETERS FOR 30 SEEDLESS WATERMELONS

Spectrum Parameters	Avg. Refraction	Avg. Firmness	MF8	Weight
CFN50	0.6810	-0.2862	0.7537	0.7829
EB85-160	0.7577	-0.3475	0.7291	0.6960

The same multiple regression techniques were applied to the seedless melon data as the Allsweet data. For the seedless data, the rejection region will be for a t value > $t_{(1-5\%)/2,\ 30} = 2.042$. The F ratio must be > 2.5 for the regression to be significant at the 5 percent level. All regressions presented for the seedless melon data are significant.

Table 12 shows the regression statistics and equation for CFN50 as a function of Average Refraction and MF8. Regression coefficients for both Average Refraction and MF8 are both significant at the 5 percent level. The correlation of this equation, 0.819, further suggests that CFN50 is a good predictor of melon maturity.

TABLE 12

CFN50 AS A FUNCTION OF AVERAGE REFRACTION AND MF8
FOR SEEDLESS WATERMELONS

CFN50 = 1.962(Avg Refraction) + 0.560(MF8) + 39.69

$r = 0.819$ $r^2 = 0.6708$ F ratio = 27.503

Variable	Variance	Standard Deviation	t Value	Confidence Level
Avg. Refraction	0.457	0.676	2.902	0.6
MF8	0.018	0.136	4.120	<0.1

Table 13 presents the multiple regression for CFN50 as a function of Average Refraction, MF8, and Average Firmness. Table 13 leads to the same conclusions as Table 5 of the Allsweet data. The t value for the regression coefficient of Average Firmness is the smallest t value for the regression. The regression coefficient of Average Firmness is not significantly different than zero at the 5 percent level. Therefore, the equation from Table 12 should be used. Also note that the coefficient for Average Firmness is a positive value which does not make physical sense according to the correlation for CFN50 with Average Firmness in Table 10.. This positive value can be contributed to correlation with the other tissue parameters.

TABLE 13

CFN50 AS A FUNCTION OF AVERAGE REFRACTION MF8, AND AVERAGE FIRMNESS FOR SEEDLESS WATERMELONS

CFN50 = 2.131(Avg Refraction) + 0.543(MF8) + 0.7106(Avg Firmness) + 37.36

$r = 0.819$ $r^2 = 0.6712$ F ratio = 17.689

Variable	Variance	Standard Deviation	t Value	Confidence Level
Avg. Refraction	1.360	1.166	1.827	7.8%
MF8	0.028	0.167	3.254	0.2%
Avg. Firmness	15.760	3.970	0.179*	85.9%

*Regression coefficient not significantly different than zero

Table 14 shows the regression statistics and equation for CFN50 as a function of Average Refraction, MF8, and weight. The regression coefficient for weight is not significantly different than zero at the 5 percent level. This insignificance of the coefficient for weight again supports my conclusion that CFN50 is not significantly dependent upon weight.

TABLE 14

CFN50 AS A FUNCTION OF AVERAGE REFRACTION, MF8, AND WEIGHT FOR SEEDLESS WATERMELONS

CFN50 = 1.487(Avg. Refraction) + 0.339(MF8) + 1.480(Weight) + 38.55

$r = 0.8355$ $r^2 = 0.6980$ F ratio = 20.03

Variable	Variance	Standard Deviation	t Value	Confidence Level
Avg. Refraction	0.532	0.729	2.040	5.0%
MF8	0.038	0.196	1.733	9.4%
Weight	0.933	0.966	1.532*	13.6%

*Regression coefficient not significantly different than zero

Table 15 contains the regression statistics and equation of EB85-160 as a function of Average Refraction and MF8. The t values show that both regression coefficients are significantly different than zero at the 5 percent level. For the seedless watermelons, this equation had the highest correlation of a spectrum parameter with the tissue parameters.

TABLE 15

EB85-160 AS A FUNCTION OF AVERAGE REFRACTION AND MF8
FOR SEEDLESS WATERMELONS

EB85-160 = 0.0211(Avg Refraction) + 0.0037(MF8) + 0.1729

$r = 0.8456$ $r^2 = 0.7150$ F ratio = 33.87

Variable	Variance	Standard Deviation	t Value	Confidence Level
Avg. Refraction	0.000	0.006	4.115	<0.1%
MF8	0.000	0.001	3.653	<0.1%

Table 16 shows the regression statistics and equation for EB85-160 as a function of Average Refraction, MF8, and Average Firmness. The regression coefficient for Average Firmness is not significantly different than zero at the 5 percent level. As with the Allsweet data, Average Firmness does not add any additional physical information to the prediction of EB85-160, and the equation in Table 15 should be used.

The data from the seedless melons further support the conclusions made from the Allsweet melon data. For both cultivars, the regression coefficients in the equations defining CFN50 and EB85-160 as functions of Average Refraction and MF8 are very similar. A possible alternative to creating separate regression equations with different coefficients for each cultivar would be to use the same regression coefficients but adjust the equation by a constant, if needed. This approach would reduce the amount of testing needed to apply impulse testing to different cultivars.

TABLE 18

AVERAGE MEASUREMENTS FOR ALLSWEET AND SEEDLESS WATERMELONS

Watermelon Cultivar	Weight (kg)	Minor Axis (cm)	Major Axis (cm)	Axis Difference (cm)
Allsweet	10.60	19.3	50.1	30.8
Seedless	8.12	23.2	29.4	6.2

Size and geometry appear to have little effect on the regression coefficients. Seedless and Allsweet cultivars are very dissimilar in size and geometry. Allsweet watermelons are larger and have an elongated shape, with the major axis much greater than the minor axis. Seedless watermelons were smaller, with a spherical shape. Table 18 contains the average size measurements for the Allsweet and seedless watermelons. Average measurements show the distinct size and geometry differences between the two cultivars.

TABLE 16

EB85-160 AS A FUNCTION OF AVERAGE REFRACTION, MF8, AND AVERAGE FIRMNESS FOR SEEDLESS WATERMELONS

EB85-160 = 0.0252(Avg Refraction) + 0.0033(MF8) + 0.0172(Avg Firmness) + 0.117

$r = 0.8477$ $r^2 = 0.7186$ F ratio = 22.14

Variable	Variance	Standard Deviation	t Value	Confidence Level
Avg. Refraction	0.000	0.009	2.899	0.6%
MF8	0.000	0.001	2.666	1.2%
Avg. Firmness	0.001	0.030	0.581*	56.6%

*Regression coefficient not significantly different than zero

Table 17 presents the regression statistics for EB85-160 as a function of Average Refraction, MF8, and weight. The regression coefficient for weight is not significantly different than zero at the 5 percent level. In fact, this coefficient does not make physical sense, because the value is a negative when the correlation between EB85-160 and weight is a positive. This multiple regression supports my early conclusion that EB85-160 is not significantly dependent upon weight.

TABLE 17

EB85-160 AS A FUNCTION OF AVERAGE REFRACTION, MF8, AND WEIGHT FOR SEEDLESS WATERMELONS

EB85-160 = 0.0215(Avg Refraction) + 0.0039(MF8) - 0.0011(Weight) + 0.1738

$r = 0.8457$ $r^2 = 0.7152$ F ratio = 21.766

Variable	Variance	Standard Deviation	t Value	Confidence Level
Avg. Refraction	0.000	0.006	3.765	<0.1%
MF8	0.000	0.002	2.538	1.6%
Weight	0.000	0.008	-0.147*	112.0%

*Regression coefficient not significantly different than zero

CFN50 Versus EB85-160

I prefer CFN50 to EB85-160 as a predictor of maturity because, it had a higher correlation in our tests of the Allsweet cultivar. Differently shaped watermelons with different average weights would most likely have a different ideal frequency range that is dominated by tissue properties. Therefore, for different cultivars an experiment similar to mine would be required to determine ideal frequency band and magnitude of a mature watermelon.

If the spectrum CFN50 is used, a much smaller test is adequate to determine the approximate frequency range of CFN50 for a mature watermelon. The same sensor unit without internal modification could be used for all cultivars. If different frequency bands are required for EB85-160, the sensor would be much more complicated requiring some method to change the summed frequency band.

EB85-160 functioned almost as well as CFN50 as a predictor of maturity, as indicated by relative correlations of the spectrum parameters to destructively measured tissue parameters found in the multiple regressions. In fact for the seedless cultivar, EB85-160 has a higher correlation than CFN50 to refraction and firmness, but the correlation value is only a few tenths higher. Furthermore, fewer seedless watermelons were tested, and the distribution of maturity levels in the seedless watermelons was less than for the Allsweet cultivar.

Recommendations

The subjective rating of maturity used in this study was imprecise. Only one researcher's opinion of taste and texture was used to judge the maturity of the melons. Guidelines for assigning the number of "days-till-ripe" were not well defined. Subjective rating did help in selecting tissue parameters which were good measures of relative maturity, but the subjective rating in our study cannot be used to assign absolute maturity rating such as "days-till-ripe" to the values given by the spectrum parameters or destructively measured tissue parameters.

Subjective judgement is difficult to use as a quantifying measurement of maturity, but it is necessary for rating the performance of a non-destructive maturity tester. Use of a taste panel will probably give the most accurate results, but I am doubtful that this degree of accuracy is necessary. In my judgement, subjective ratings are needed only to draw a few distinct lines on maturity levels. These levels can then be matched with the tissue parameters or even directly to CFN50.

The summer 1990 study did not answer the question of what effect an overripe watermelon has on the impulse frequency response spectrum. In this study, only two melons were judged as overripe. Therefore, I was unable to determine statistically how the overripe tissue affected the spectrum. It does appear, however, that CFN50 and EB85-160 both decrease after the watermelon reached peak maturity.

Another useful application of the impulse frequency response sensor would be the identification of watermelons that are degrading due to prolonged storage. I have not tested watermelons that have been stored for more than 2 days. However, I would expect that degradation due to storage will cause a decrease in the CFN50 frequency. Yamamoto (1980) found that natural frequencies of watermelons decreased significantly over a period of three weeks, while mass did not.

Suggestions for a Field Unit

A field unit could be built that would apply impulse testing and then calculate the spectrum parameter, CFN50. Further testing at the prototype level is required, but most of the further research should be focused on designing a field unit. Such a field unit would need to be portable and could probably be contained in a single hand-held unit.

Energy for the impulse could come from a spring loaded-trigger, solenoid device, or other mechanism that can generate at least as much energy as the current prototype. Increasing the energy input would create a larger measurable response which would decrease noise degradation of the signal.

Circuitry for the unit should be capable of recording the impulse frequency response, calculating the spectrum, and calculating CFN50 or EB85-160. Specific circuitry components will not be discussed, but the circuit should meet the following criteria:

1. Sampling frequency greater than 1000 Hz.
2. Low-pass filter with cutoff frequency of 500 Hz.
3. Spectrum calculation to a resolution of less than 2.441 Hz.

Changing the Sampling Frequency

Sampling frequency in the summer 1990 experiment was set at 5000 Hz to ensure adequate resolution of the signal. One thousand points, or 0.2 seconds of the impulse frequency response, was used to obtain the spectra. Spectra were calculated using a 2048-point FFT to achieve a spectrum resolution of 2.441 Hz. The amount of data used to obtain the spectrum can be decreased by reducing the sampling frequency. Reducing the sampling frequency will reduce the amount of points needed in the FFT to have the same or higher resolution of the spectrum. Resolution refers to the frequency increments between the spectrum samples.

Theoretically, a sampling frequency of 1000 Hz is required to distinguish a 500 Hz signal. Therefore, the minimum sampling frequency possible is 1000 Hz. This minimum assumes that an ideal low-pass filter could be designed which would not interfere with signal content below 500 Hz and would completely remove all of the signal frequencies above 500 Hz. Of course, an ideal filter is a physical impossibility, and the quality of the filter circuit designed would depend largely on cost. In the summer 1990 test, the low-pass filter removed as much as 20% of the signal at 500 Hz.

With a sampling frequency of 1000 Hz, 200 points of the impulse frequency response are required for the same time window as used in this study. A 512-point FFT, rather than a 2048-point FFT, could be used to attain a spectrum resolution of 1.95 Hz.

TABLE 19

EFFECT OF SPECTRUM RESOLUTION ON CORRELATION OF CFN50 AND AVERAGE REFRACTION

Sampling Frequency	Points FFT	Correlation Avg R.	Spectrum Resolution
5000	2048	0.6745	2.441
5000	1024	0.5659	4.883
5000	512	0.5500	9.766

Table 19 shows the effect on correlation of decreasing the spectrum resolution. The data for Table 19 were calculated from the original impulse frequency response signals using different numbers of FFT points. Both 2048 and 1024-point spectra contain all 1000 original points. The 512-point spectrum contains only the first 512 original points.

Correlation decreased as the number of spectrum points decreased. This result was expected, because with the decrease in the resolution of the spectrum, CFN50 becomes less precise. Reduction in the performance of CFN50 is analogous to the loss of accuracy when distance measurements are rounded from the nearest inch to the nearest foot.

Summary

Market quality of watermelons depends largely on the maturity when picked in the field. Watermelons do not mature significantly after picking, and therefore should be picked at peak maturity. Maturity of a watermelon is difficult to determine from outward characteristics. Currently, there is no objective way to determine maturity.

Research was conducted in the summer of 1990 to determine an objective maturity testing method using impulse testing. A sensor unit was developed which collects the impulse frequency response by powering a solenoid to generate a mechanical impulse and then collect the vibration response of the watermelon with a piezoelectric transducer. Frequency spectrum of the impulse frequency response was calculated with the Fast Fourier Transform. Energy content of the spectrum from 0 to 500 Hz was normalized to one. Spectrum parameters were calculated from this normalized spectrum.

Two spectrum parameters of the impulse frequency response were found to have significant correlation with destructively measured parameters of maturity. Highest correlations of spectrum parameters were with combinations of optical refraction and Modulus of Firmness at 8 mm (penetration force versus penetration depth of the outer white tissue, "rind"). To obtain correlation values, multiple regression was used to combine the tissue parameters into a single prediction equation of the spectrum parameters. Hypothesis testing using the t test was used to judge the significance of the regression coefficients found in multiple regressions. In the t tests, both Average Refraction and Modulus of Firmness at 8 mm had regression coefficients significantly different than zero at the 5 percent level, and weight had a regression coefficient not significantly different than 0 at the 5 percent level.

The two spectrum parameters were:

1. Center frequency of the narrowest 50 percent energy band (CFN50)

2. Energy content of the frequency band from 85.45 to 158.69 Hz (EB85-160)

Spectrum parameters were initially found by testing 74 watermelons of the Allsweet cultivar. These parameters were then tested on 30 watermelons of a seedless variety. Four regression equations relating CFN50 and EB85-160 as functions of Average Refraction and Modulus of Firmness at 8 mm (MF8) are listed below:

Allsweet Watermelons:

1. CFN50 = 2.602(Avg. Refraction) + 0.3513(MF8) + 42.76 ($r = 0.734$)

2. EB85-160 = 0.0214(Avg. Refraction) + 0.0037(MF8) + 0.094 ($r = 0.634$)

Seedless Watermelons:

1. CFN50 = 1.962(Avg. Refraction) + 0.560(MF8) + 39.69 ($r = 0.819$)

2. EB85-160 = 0.0211(Avg. Refraction) + 0.0037(MF8) + 0.1729 ($r = 0.846$)

The spectrum parameters of the impulse response found in this study have proven to be good measures of maturity. The ability to model the spectrum parameters, CFN50 and EB85-160, as a function of optical refraction (crude sugar content) and firmness verifies the spectrum parameters as a measure of ripeness.

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APPENDICES

APPENDIX A

IMPULSE FREQUENCY RESPONSE SENSOR SPECIFICATIONS

Appendix A contains working drawings to build the plexiglass portion of the impulse frequency response sensor, manufacturer's information on the solenoid, and data taken during the pendulum test. The piezoelectric transducer and solenoid are mounted in the plexiglass unit. When testing frequency response, the sensor unit should be held in the vertical plane, with the transducer resting against the watermelon surface.

Manufacturer's name and description of the solenoid are given below:

Manufacturer: Guardian Electric Manufacturing Co. Woodstock, Illinois 60098

Description: TP 8 x 9 Inter. 24 DC, Tubular Solenoid

Pendulum Test of Energy Created by Solenoid

Pendulum test section in the main body of this thesis describes the techniques used to determine the amount of energy transferred to the watermelon by the solenoid. Table 20 contains data taken when calibrating the piezoelectric transducer to measure the amount of energy transferred by the pendulum. Peak voltage response of the transducer is directly proportional to the energy of the pendulum impact.

TABLE 20

AMPLITUDE OF PENDULUM IMPACT FOR GIVEN PENDULUM DISPLACEMENTS

Distance (mm)	Peak Signal (volts)	Energy (joules)
129.20	1.475	0.000294
129.20	1.397	0.000294
129.20	1.420	0.000294
129.20	1.191	0.000294
136.40	1.479	0.000328
136.40	1.495	0.000328
136.40	1.511	0.000328
136.40	1.350	0.000328
136.40	1.239	0.000328
136.40	1.415	0.000328
145.99	1.639	0.000376
145.99	1.431	0.000376
145.99	1.447	0.000376
145.99	1.369	0.000376
145.99	1.383	0.000376
160.02	1.735	0.000453
160.02	1.671	0.000453
160.02	1.767	0.000453
160.02	1.671	0.000453
160.02	1.671	0.000453
160.02	1.719	0.000453
170.90	1.639	0.000518
170.90	1.895	0.000518
170.90	1.751	0.000518
170.90	1.687	0.000518
170.90	1.751	0.000518
170.90	1.863	0.000518

TABLE 20 (Continued)

Distance (mm)	Peak Signal (volts)	Energy (joules)
179.93	1.927	0.000576
179.93	1.767	0.000576
179.93	1.783	0.000576
179.93	1.735	0.000576
179.93	2.055	0.000576
179.93	1.719	0.000576
186.70	1.870	0.000621
186.70	2.190	0.000621
186.70	2.222	0.000621
186.70	2.344	0.000621
186.70	2.094	0.000621
186.70	1.934	0.000621
197.51	1.955	0.000697
197.51	2.270	0.000697
197.51	2.286	0.000697
197.51	2.158	0.000697
197.51	1.934	0.000697
197.51	2.355	0.000697

Using Equation (4), page 18, I created Table 21 by recording the voltage generated from the impact of the pendulum on the transducer. Calculated from Table 21 is the average energy of impact and standard deviation of the impact energy.

Average Energy of Impact = 0.000785 J

Standard Deviation = 0.000030

TABLE 21

ENERGY TRANSFERRED TO PENDULUM FROM SOLENOID

Peak Signal (volts)	Energy (joules)
1.702	0.000736
1.846	0.000764
1.902	0.000775
1.838	0.000763
2.158	0.000826
1.998	0.000795
1.902	0.000775
2.094	0.000814
1.934	0.000782
1.838	0.000763
1.998	0.000795
2.254	0.000846
1.854	0.000766
1.794	0.000754
2.158	0.000826

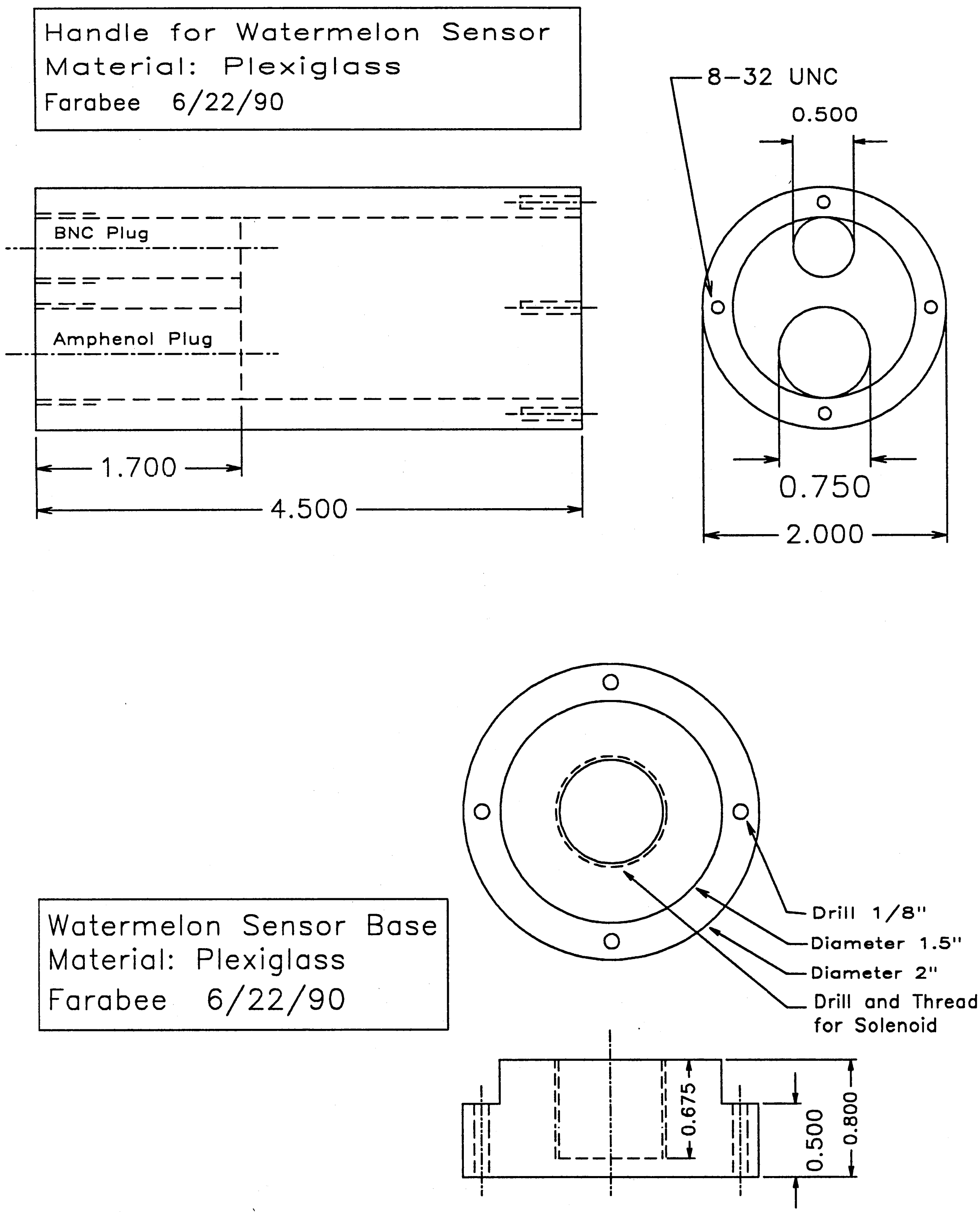

Figure 10. Design drawings for prototype impulse response sensor

APPENDIX B

4th-ORDER LOW-PASS FILTER SPECIFICATIONS

Appendix B contains the circuit diagram and performance curve for the 4th-order low-pass filter used in the summer 1990 study. The low-pass filter was designed to be used with a sampling frequency of 5000 Hz. Tests on the filter show that it passes 80% of signal at 500 Hz and less than 20% of signal at 2500 Hz.

Performance curve shows the output of the filter for different frequency sine waves with peak amplitudes of 5 volts. Amplifier portion of the filter was set to give an approximately gain of 3.

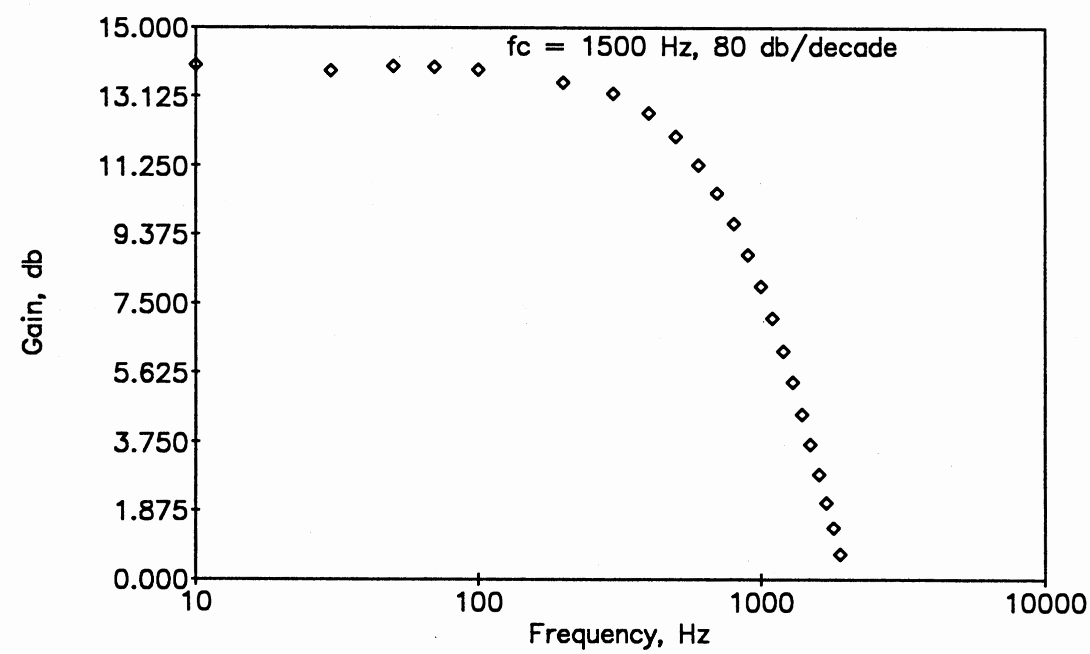

Figure 11. Performance curve for 4th-order low-pass filter

4th–Order Low–Pass Filter and Amplifier

Filter is made from one chip (LM324). Voltage supplied is –15V and +15V.
Corner frequency of circuit is 1500 Hz (fc = 1/(2pi*C1*R3)).
Gain of the circuit is dependent on RR1 (K = R3/RR1).

C1 = 0.01 uF
R1 = 100 kohmns R2 = 100 kohms R3 = 100 kohmns RR1 = 10 to 100 kohmns

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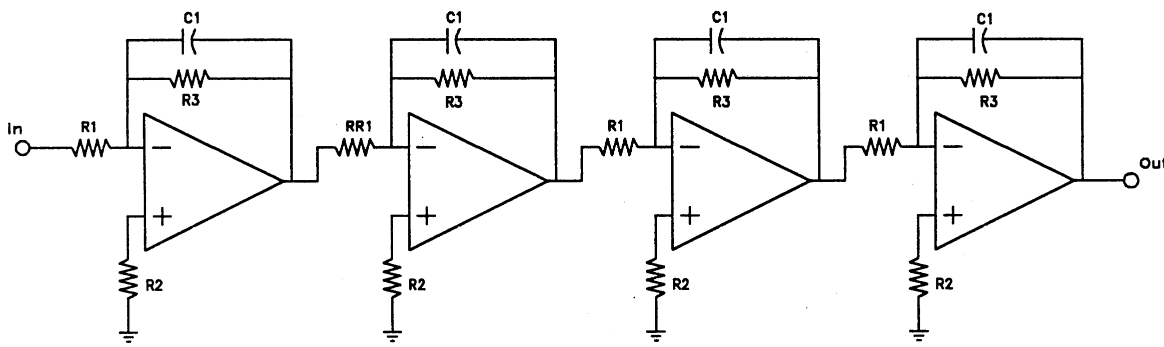

Figure 12. Circuit diagram for 4th-order low-pass filter

APPENDIX C

ALLSWEET WATERMELONS MATURITY DATA

Appendix C contains the data for the Allsweet cultivar collected during the summer 1990 watermelon maturity study. Table 22 presents the data taken during the test. Table 23 shows the correlation of the data with the other data values. Definitions for abbreviations used in Table 22 and 23 can be found in the list of nomenclature.

TABLE 22

WATERMELON MATURITY TEST DATA FOR ALLSWEET CULTIVAR

Data in this table are for watermelons of the Allsweet cultivar, picked during August 1990 near Hydro, Oklahoma.

num	Sub Mat.	Minor cm	Major cm	Wt kg	PRT kg	PT1 kg	PT2 kg	PH kg
1	over 5	20.00	46.04	9.71	5.75	1.95	1.90	1.90
2	over 3	19.05	51.75	11.00	5.13	1.70	1.40	1.65
3	over 3	19.37	49.85	10.60	3.60	1.24	0.98	1.23
4	over 5	19.80	45.40	9.49	2.98	1.93	1.50	1.60
5	over 5	17.78	48.90	9.41	5.74	1.93	2.01	2.45
6	3 to 5	18.10	45.09	8.72	4.78	1.53	1.24	1.33
7	over 5	18.10	46.04	8.19	4.05	1.95	1.78	2.10
8	early m	18.42	47.94	9.17	3.53	1.60	1.10	1.03
9	over 5	18.10	46.99	8.68	6.38	2.23	1.90	2.25
10	3 to 5	17.78	45.72	8.25	3.21	1.26	1.25	1.33
11	over 5	17.15	42.55	7.38	2.92	1.85	1.48	1.90
12	1 to 3	18.26	51.44	10.02	2.93	1.61	1.29	1.15
13	immature	17.78	52.71	11.00	3.95	2.06	1.69	1.83
14	immature	20.00	54.29	11.96	3.43	1.60	1.66	1.98
15	3 to 5	17.15	50.96	9.11	3.01	1.96	1.39	1.83
16	3 to 5	18.10	43.18	8.52	2.19	1.56	1.73	1.65
17	1 to 3	18.42	49.85	9.41	2.23	1.76	1.58	1.68
18	over 3	16.19	47.31	8.28	4.55	1.40	1.45	1.95
19	1 to 3	19.37	46.67	9.20	2.38	1.61	1.49	2.08
20	edible	19.37	46.83	10.75	2.64	1.78	1.69	2.05
21	3 to 5	18.10	46.83	8.50	2.41	1.25	1.33	1.35
22	over 3	17.62	45.40	8.10	2.76	1.74	1.69	1.80
23	mature	20.00	46.67	9.88	2.53	1.10	0.83	0.90
24	mature	17.62	48.26	8.39	3.01	1.01	0.50	0.80
25	over 3	17.15	48.10	7.50	2.86	1.78	1.79	1.90
26	1 to 3	17.78	47.15	7.46	2.63	0.63	0.86	0.88
27	mature	18.57	48.74	9.51	2.36	1.13	0.95	0.88
28	over 3	18.42	44.29	8.52	3.13	1.49	1.79	1.98
29	3 to 5	17.07	47.15	7.60	3.18	1.18	1.06	1.08
30	1 to 3	17.30	51.75	9.39	2.45	1.40	1.36	1.08
31	1 to 2	17.78	48.90	9.26	2.28	1.24	0.83	1.10
32	over 5	17.46	48.42	8.58	2.76	1.73	1.50	1.98
33	early mat	18.10	42.55	8.44	3.18	1.31	1.55	1.40
34	over 3	19.37	46.36	9.54	2.83	1.78	1.85	2.50
35	1 to 2	18.89	45.24	8.89	2.94	1.86	1.74	1.75

TABLE 22 (Continued)

num	Sub Mat.	Minor cm	Major cm	Wt kg	PRT kg	PT1 kg	PT2 kg	PH kg
36	2 to 3	17.78	39.85	6.93	2.94	1.84	1.55	1.48
37	over 5	16.67	45.88	7.58	5.46	1.88	1.54	1.78
38	over 5	18.42	42.70	8.24	3.53	1.68	1.78	2.40
39	early mat	19.21	45.09	9.44	3.45	1.28	1.09	1.08
40	mature	18.26	46.83	8.13	3.28	1.60	1.23	1.20
41	over 3	17.94	47.63	9.34	2.89	1.44	1.38	1.33
42	early mat	21.27	37.78	9.61	3.00	1.50	1.19	1.73
43	1 to 2	20.00	53.50	11.91	3.44	1.53	1.51	1.20
44	mature	20.00	48.26	9.87	3.33	1.16	1.09	0.80
45	3 to 5	20.32	53.66	13.03	3.66	1.49	1.60	1.50
46	early mat	20.48	58.42	13.86	3.70	1.48	1.38	1.30
47	mature	21.59	58.10	14.46	4.49	1.70	1.60	1.53
48	1 to 2	21.01	61.60	16.16	2.75	1.76	1.91	1.65
49	mature	20.48	57.15	13.07	3.90	1.23	0.76	1.00
50	mature	20.48	53.98	11.63	2.85	0.94	0.83	1.05
51	mature	20.00	54.29	12.14	2.88	1.14	0.83	0.93
52	3 to 5	20.16	59.37	15.25	2.88	1.50	1.40	1.53
53	2 to 3	18.89	54.13	11.61	2.73	1.76	1.36	1.55
54	very mat	19.69	57.15	12.56	2.69	1.46	1.15	1.05
55	mature	22.86	54.45	14.11	2.83	1.26	1.05	1.13
56	mature	22.23	44.77	11.68	3.04	1.29	1.26	1.18
57	mature	20.00	54.45	12.90	4.53	1.57	1.53	1.33
58	mature	20.16	47.15	11.43	3.25	1.21	0.77	1.00
59	early mat	20.48	52.23	12.98	2.59	1.65	1.39	1.83
60	late mat	20.16	51.12	10.62	3.89	0.98	0.69	0.93
61	mature	21.27	50.17	11.81	2.88	1.35	1.12	1.14
62	mature	20.80	54.13	12.90	2.76	1.33	1.10	1.08
63	mature	20.16	55.09	13.40	3.90	1.05	0.99	1.30
64	mature	19.05	52.39	10.81	4.15	1.47	1.32	1.10
65	mature	20.96	52.71	12.95	3.49	1.27	0.95	1.07
66	mature	21.91	64.77	18.75	3.95	1.49	0.97	1.10
67	mature	20.00	54.93	12.22	3.41	1.67	1.07	1.20
68	over mat	19.69	54.61	11.48	3.14	1.39	0.86	0.94
69	mature	21.43	55.56	14.26	4.54	1.55	1.10	1.00
70	mature	20.00	55.88	11.78	3.33	1.48	0.83	0.99
71	rmature	21.27	47.31	11.91	2.13	1.03	1.07	1.23
72	mature	19.53	51.91	11.20	3.85	1.12	1.02	1.01
73	mature	19.53	52.39	9.71	2.59	0.97	1.07	0.98
74	mature	21.43	59.06	13.81	3.50	1.06	0.94	1.05

TABLE 22 (Continued)

num	SRT Rdiv	ST1 Rdiv	ST2 Rdiv	SH Rdiv	MF8 kg/cm	p8 kg	MF20 kg/cm	p20 kg
1	5.10	7.28	7.48	7.30	24.708	12.530	8.862	3.320
2	5.37	7.67	9.53	8.80	22.064	12.350	9.046	3.350
3	5.93	8.35	9.48	9.87	22.503	10.710	8.758	3.930
4	5.07	6.57	7.73	7.60	28.081	12.310	9.229	2.860
5	4.85	6.53	7.05	6.50	26.642	14.300	15.055	7.640
6	6.23	8.95	10.00	9.95	22.099	8.460	14.763	5.850
7	5.40	6.75	7.78	7.60	25.430	12.890	8.701	3.650
8	6.65	9.45	10.48	10.60	23.015	9.330	12.161	5.170
9	4.87	6.55	6.70	6.60	31.924	12.680	13.620	4.440
10	6.30	8.53	9.68	9.70	20.187	8.060	9.024	3.630
11	5.85	7.30	8.10	8.10	17.419	7.990	8.384	3.360
12	6.10	8.40	9.95	10.20	31.072	12.167	11.065	4.537
13	6.60	9.58	9.70	9.35	31.637	11.030	9.027	2.737
14	7.55	9.45	10.30	10.00	31.131	13.675	11.215	5.277
15	6.60	8.63	9.55	9.20	29.143	14.093	10.388	3.937
16	6.30	9.08	9.85	9.30	24.983	12.800	11.245	5.277
17	7.25	9.70	10.43	10.30	23.392	9.680	16.869	5.113
18	6.65	8.88	10.00	9.70	30.946	15.607	11.703	5.450
19	6.80	9.28	10.23	10.20	19.089	7.820	14.892	3.783
20	6.43	8.63	9.15	8.87	23.633	9.933	13.098	5.360
21	6.53	8.95	9.80	8.90	25.476	12.143	11.417	4.943
22	5.43	7.00	8.53	8.45	27.781	13.533	10.649	5.427
23	7.63	10.15	10.98	11.15	29.904	12.233	14.497	6.723
24	6.93	9.78	11.58	12.10	24.619	6.487	17.218	6.570
25	5.38	7.38	8.53	8.40	23.654	17.360	9.954	4.500
26	6.85	8.48	10.78	10.50	24.524	9.860	14.015	7.840
27	7.60	10.50	11.15	11.00	26.153	10.147	17.936	6.233
28	5.85	7.65	8.53	8.10	23.800	11.480	8.387	3.993
29	7.20	10.25	10.68	10.80	14.548	11.127	4.211	6.783
30	7.45	9.30	10.70	10.70	27.483	9.847	13.858	5.423
31	6.65	9.30	10.15	9.75	30.934	10.843	20.010	7.160
32	5.75	7.78	8.85	8.40	24.070	12.353	12.211	4.390
33	7.00	9.63	10.20	10.20	30.013	11.680	9.625	2.327
34	6.30	8.28	8.80	8.10	30.356	10.720	12.716	2.873
35	6.80	9.45	10.05	9.60	29.839	11.285	12.450	2.797
36	6.75	9.20	10.63	10.40	30.767	9.440	13.803	3.697
37	4.55	6.45	7.55	7.55	39.737	14.660	15.196	4.250
38	6.48	8.53	10.25	10.50	38.372	16.660	16.627	8.250

TABLE 22 (Continued)

num	SRT Rdiv	ST1 Rdiv	ST2 Rdiv	SH Rdiv	MF8 kg/cm	p8 kg	MF20 kg/cm	p20 kg
39	6.68	9.40	11.35	11.40	33.449	10.867	12.451	3.150
40	7.65	10.05	10.80	10.55	31.506	7.800	11.807	2.853
41	5.38	7.40	8.85	8.80	26.954	11.807	11.118	3.397
42	6.53	9.93	9.88	9.50	29.478	8.125	10.909	20.770
43	6.35	9.25	10.23	10.30	30.610	8.980	13.319	3.050
44	6.80	9.73	11.60	11.40	30.794	9.707	8.622	2.367
45	6.53	9.40	10.15	10.40	41.485	15.167	18.282	7.260
46	7.13	9.80	10.70	10.80	37.198	14.600	17.825	5.793
47	7.50	10.08	11.35	10.60	33.707	13.733	17.708	5.703
48	6.75	9.08	10.25	9.80	33.010	14.500	15.320	4.668
49	7.35	10.70	12.00	12.00	41.522	13.020	19.792	4.533
50	7.65	10.35	11.75	10.60	40.681	12.620	13.249	4.180
51	7.75	10.50	11.00	10.50	33.350	10.167	12.953	3.007
52	6.85	9.78	11.15	11.05	39.045	15.973	15.526	5.350
53	6.63	8.75	9.90	9.55	30.342	11.973	11.426	2.430
54	8.68	12.05	12.25	12.10	39.273	11.100	12.664	2.633
55	7.85	11.65	12.18	11.30	41.876	12.307	13.003	3.333
56	8.18	11.28	12.60	12.40	40.249	10.653	16.527	3.090
57	8.00	10.10	12.15	12.70	44.814	15.120	17.654	5.350
58	7.90	10.65	12.33	11.15	41.387	10.720	16.265	3.637
59	6.58	9.40	10.50	10.05	37.797	12.107	11.123	2.400
60	7.90	10.65	11.98	11.25	37.799	9.600	17.821	4.110
61	8.58	11.13	11.90	11.65	39.778	9.350	15.836	3.547
62	7.30	10.70	12.35	12.15	38.284	12.300	23.129	5.120
63	8.68	10.83	11.88	11.75	36.293	10.620	14.769	3.633
64	7.53	10.45	11.33	11.05	42.145	13.020	19.001	4.017
65	7.90	10.58	12.00	12.10	26.909	9.033	12.990	4.190
66	7.23	10.25	12.15	12.05	38.307	15.453	17.719	4.190
67	6.93	9.10	11.25	11.15	36.020	12.380	12.895	2.733
68	8.18	11.23	12.65	12.20	46.478	16.393	19.584	4.667
69	7.83	10.93	12.30	12.55	38.296	12.327	24.949	8.433
70	6.98	10.08	12.20	11.70	40.357	12.733	18.131	4.323
71	8.15	11.40	12.70	12.75	29.631	9.500	16.961	3.427
72	7.33	9.83	11.48	11.35	30.902	14.040	13.718	4.857
73	7.03	10.45	11.33	9.80	38.326	14.020	18.064	5.983
74	8.15	11.03	11.68	11.60	28.087	9.487	16.963	4.603

TABLE 22 (Continued)

num	MF40 kg/cm	p40 kg	Avg F. kg	Avg R. Rdiv	CFN50 Hz	EB85-160
1	4.264	4.610	1.92	7.35	75.68	0.381
2	3.764	1.240	1.58	8.67	73.24	0.362
3	4.062	1.340	1.15	9.23	72.02	0.383
4	4.807	1.550	1.68	7.30	70.80	0.282
5	5.058	1.640	2.13	6.69	75.68	0.318
6	5.894	1.470	1.37	9.63	68.36	0.311
7	4.203	1.120	1.94	7.38	72.02	0.337
8	3.142	1.330	1.24	10.18	76.90	0.399
9	7.286	2.110	2.13	6.62	73.24	0.357
10	2.769	0.940	1.28	9.30	72.02	0.300
11	3.973	1.470	1.74	7.83	54.93	0.219
12	3.282	1.330	1.35	9.52	81.79	0.436
13	5.265	1.577	1.86	9.54	76.90	0.440
14	5.580	2.133	1.75	9.92	85.45	0.446
15	5.102	1.333	1.73	9.13	73.24	0.442
16	5.580	2.133	1.65	9.41	75.68	0.366
17	4.348	1.233	1.67	10.14	74.46	0.326
18	5.445	1.793	1.60	9.53	80.57	0.327
19	4.677	1.627	1.73	9.90	76.90	0.424
20	3.824	1.193	1.84	8.88	80.57	0.454
21	4.286	1.383	1.31	9.22	73.24	0.288
22	5.122	2.047	1.74	7.99	78.13	0.365
23	3.259	1.017	0.94	10.76	90.33	0.493
24	2.782	0.857	0.77	11.15	83.01	0.432
25	5.036	2.000	1.82	8.10	80.57	0.459
26	2.346	0.797	0.79	9.92	84.23	0.411
27	2.402	0.827	0.99	10.88	76.90	0.388
28	5.743	1.853	1.75	8.09	74.46	0.432
29	1.107	1.147	1.11	10.58	86.67	0.451
30	3.641	1.200	1.28	10.23	79.35	0.446
31	3.878	1.100	1.06	9.73	80.57	0.401
32	5.515	1.430	1.74	8.34	73.24	0.402
33	6.302	1.343	1.42	10.01	72.02	0.380
34	7.700	1.550	2.04	8.39	69.58	0.361
35	7.805	1.537	1.78	9.70	69.58	0.277
36	5.476	1.313	1.62	10.08	76.90	0.457
37	5.547	1.253	1.73	7.18	70.80	0.374
38	7.695	1.817	1.95	9.76	74.46	0.370

TABLE 22 (Continued)

num	MF40 kg/cm	p40 kg	Avg F. kg	Avg R. Rdiv	CFN50 Hz	EB85-160
39	4.916	0.917	1.15	10.72	74.46	0.410
40	4.818	1.100	1.34	10.47	75.68	0.431
41	4.152	1.200	1.38	8.35	72.02	0.432
42	3.799	1.100	1.47	9.77	76.90	0.437
43	5.623	1.503	1.41	9.93	69.58	0.339
44	3.591	0.883	1.02	10.91	81.79	0.453
45	7.181	1.300	1.53	9.98	84.23	0.513
46	7.145	1.533	1.39	10.43	81.79	0.434
47	7.038	1.450	1.61	10.68	86.67	0.539
48	6.978	1.353	1.77	9.71	89.11	0.597
49	6.378	1.020	1.00	11.57	95.21	0.348
50	4.370	0.783	0.94	10.90	85.45	0.505
51	3.307	0.627	0.97	10.67	83.01	0.440
52	5.345	1.140	1.48	10.66	81.79	0.340
53	6.063	1.160	1.56	9.40	76.90	0.384
54	6.408	1.040	1.22	12.13	89.11	0.455
55	5.390	0.930	1.15	11.71	80.57	0.439
56	5.891	0.893	1.24	12.09	84.23	0.517
57	6.290	1.327	1.48	11.65	89.11	0.511
58	4.201	0.783	0.99	11.38	85.45	0.477
59	4.248	0.900	1.62	9.98	85.45	0.522
60	4.197	0.817	0.87	11.29	92.77	0.551
61	5.761	0.940	1.20	11.56	86.67	0.544
62	7.910	1.287	1.17	11.73	87.89	0.548
63	4.432	0.867	1.11	11.49	91.55	0.522
64	6.029	1.137	1.30	10.94	84.23	0.445
65	5.056	0.867	1.10	11.56	76.90	0.402
66	5.368	0.927	1.19	11.48	81.79	0.463
67	4.656	0.923	1.31	10.50	87.89	0.537
68	4.819	0.883	1.06	12.03	93.99	0.555
69	7.609	1.387	1.22	11.93	91.55	0.514
70	6.448	1.433	1.10	11.33	84.23	0.516
71	5.740	0.957	1.11	12.28	85.45	0.457
72	5.160	1.140	1.05	10.89	80.57	0.380
73	5.276	1.347	1.01	10.53	87.89	0.457
74	6.363	1.633	1.02	11.44	78.13	0.416

TABLE 23

CORRELATION OF DATA FOR ALLSWEET CULTIVAR

	CFN50	EB85-160	Avg F.	Avg R.	Wt	MF8
CFN50	1.0000					
EB85-160	0.7802	1.0000				
Avg F.	-0.5104	-0.3491	1.0000			
Avg R.	0.6745	0.5645	-0.7511	1.0000		
Wt	0.5308	0.4965	-0.2460	0.5535	1.0000	
MF8	0.5997	0.5408	-0.2523	0.5226	0.5717	1.0000
p8	0.2567	0.1430	0.2993	-0.1379	0.2636	0.4464
MF20	0.5289	0.4062	-0.3459	0.5435	0.4690	0.6090
p20	0.1261	0.0278	-0.1206	0.0016	-0.1269	-0.0891
MF40	0.0452	0.1055	0.3629	0.0735	0.3610	0.4896
p40	-0.2596	-0.2731	0.5944	-0.5321	-0.2158	-0.2671
PRT	-0.0744	-0.1196	0.2972	-0.3018	0.0614	0.1166
PT1	-0.4604	-0.2710	0.8964	-0.6497	-0.1475	-0.1467
PT2	-0.4679	-0.3118	0.9488	-0.6974	-0.2294	-0.2446
PH	-0.4959	-0.3741	0.9482	-0.7414	-0.2923	-0.2914
SRT	0.6444	0.5425	-0.6471	0.9279	0.4984	0.4698
ST1	0.6451	0.5342	-0.6875	0.9619	0.5396	0.5026
ST2	0.6847	0.5790	-0.7641	0.9913	0.5525	0.5436
SH	0.6470	0.5405	-0.7465	0.9773	0.5307	0.4858

	p8	MF20	p20	MF40	p40	PRT
p8	1.0000					
MF20	0.1639	1.0000				
p20	-0.0261	0.1750	1.0000			
MF40	0.4031	0.4308	-0.1817	1.0000		
p40	0.2482	-0.2390	-0.0490	0.2455	1.0000	
PRT	0.2680	0.0366	-0.0273	0.2297	0.3737	1.0000
PT1	0.2543	-0.2652	-0.2297	0.3415	0.5065	0.3518
PT2	0.3227	-0.3445	-0.1193	0.3846	0.6195	0.2482
PH	0.2601	-0.3490	-0.0228	0.2981	0.5331	0.2443
SRT	-0.1826	0.4647	-0.0235	0.0674	-0.4913	0.3301
ST1	-0.1749	0.4993	-0.0011	0.0913	-0.4769	-0.3161
ST2	-0.1044	0.5512	-0.0041	0.0679	-0.5526	-0.3047
SH	-0.1282	0.5403	0.0095	0.0581	-0.5270	-0.2662

TABLE 23 (Continued)

	PT1	PT2	PH	SRT	ST1	ST2	SH
PT1	1.0000						
PT2	0.7941	1.0000					
PH	0.7545	0.8598	1.0000				
SRT	-0.5977	-0.5930	0.6177	1.0000			
ST1	-0.6081	-0.6356	0.6721	0.9465	1.0000		
ST2	-0.6647	-0.7119	0.7492	0.9059	0.9353	1.0000	
SH	-0.6299	-0.6932	0.7478	0.8718	0.8906	0.9685	1.0000

APPENDIX D

SEEDLESS WATERMELON MATURITY DATA

Appendix D contains the data for the seedless watermelons collected during the summer 1990 watermelon maturity study. Table 24 presents the data taken during the test. Table 25 shows the correlation values of the data with the other data values. Definitions of abbreviations used in Table 24 and 25 can be found in the list of nomenclature.

TABLE 24

WATERMELON MATURITY TEST DATA FOR SEEDLESS CULTIVAR

Data in this table are for watermelons of a seedless cultivar, picked during August 1990 near Hydro, Oklahoma.

num	Sub Mat.	Minor cm	Major cm	Wt kg	PRT kg	PT1 kg	PT2 kg	PH kg
1	none	20.64	25.08	5.38	1.38	1.15	1.40	2.20
2	immature	21.59	26.04	5.91	3.85	2.50	2.50	3.00
3	immature	20.64	26.99	5.98	5.10	1.85	1.75	2.80
4	none	24.13	28.89	8.15	3.28	1.35	1.23	1.40
5	immature	20.96	28.58	6.61	2.75	2.05	1.60	2.30
6	early mat	24.77	27.62	8.45	3.78	1.05	1.00	1.15
7	none	22.38	28.42	7.16	2.28	1.18	1.43	1.65
8	none	22.38	27.78	7.55	3.05	1.73	1.46	2.00
9	none	21.59	28.42	6.63	3.19	0.99	0.93	1.13
10	none	20.80	26.67	5.68	2.66	1.49	1.44	2.38
11	over 3	21.59	29.69	7.46	4.63	1.50	1.51	1.70
12	mature	23.50	30.32	8.32	3.41	1.34	1.00	1.35
13	mature	21.91	28.89	7.19	3.56	1.21	1.21	1.20
14	mature	21.43	30.16	7.58	3.16	1.61	1.48	1.78
15	mature	24.77	30.64	9.65	2.41	1.21	1.11	1.50
16	mature	25.24	31.75	9.98	2.89	1.11	1.30	1.60
17	mature	23.02	30.96	8.50	2.90	1.35	1.15	2.00
18	over 2	23.50	32.39	8.55	3.26	1.32	1.48	2.03
19	over 5	23.50	29.53	8.45	3.41	1.49	1.76	4.03
20	mature	21.11	27.62	6.56	3.05	1.38	1.35	1.58
21	early mat	24.45	32.54	10.05	3.88	1.53	1.66	2.00
22	over 2	22.70	29.85	7.95	2.26	1.49	1.45	2.55
23	over 2	21.75	29.53	7.57	3.14	1.78	1.66	2.15
24	early mat	24.77	30.32	9.70	4.71	1.47	1.47	2.20
25	mature	23.65	30.00	8.64	2.75	1.16	1.43	2.35
26	over 3	22.07	28.42	7.06	3.14	1.51	1.60	2.35
27	over 3	24.77	31.75	9.61	2.53	1.10	1.20	1.63
28	early mat	26.35	33.66	10.55	3.85	1.30	1.70	2.34
29	early mat	25.88	28.26	9.98	2.65	1.49	1.05	1.58
30	early mat	28.89	30.80	12.75	3.35	1.45	1.51	1.50

TABLE 24 (Continued)

num	SRT Rdiv	ST1 Rdiv	ST2 Rdiv	SH Rdiv	MF8 kg/cm	p8 kg	MF20 kg/cm	p20 kg
1	4.90	7.20	8.60	9.20	18.105	7.417	7.626	2.310
2	4.75	5.60	5.50	5.20	19.361	7.858	4.823	1.800
3	5.00	7.05	7.50	7.10	23.251	9.483	9.412	3.757
4	6.85	9.60	11.05	11.60	25.355	7.423	9.085	2.183
5	4.50	6.70	7.00	6.50	23.534	10.250	11.084	3.100
6	7.30	9.58	11.33	10.70	23.082	9.150	17.716	6.383
7	6.50	9.35	10.40	10.60	19.653	6.670	12.572	4.400
8	5.45	8.65	9.08	8.60	23.484	8.413	18.359	8.160
9	6.90	10.05	10.93	10.90	20.239	7.620	12.974	4.260
10	5.63	7.85	8.43	8.85	20.444	7.593	13.354	5.247
11	5.35	8.83	9.45	9.40	18.752	8.330	10.370	3.203
12	6.40	9.20	10.75	11.15	24.192	8.233	16.381	6.927
13	7.15	9.95	10.40	10.17	14.211	5.820	13.333	4.387
14	6.58	10.38	12.20	12.35	30.118	9.780	12.039	2.840
15	7.33	10.75	11.53	11.80	39.749	8.407	7.941	2.223
16	7.40	10.00	11.30	11.30	33.508	8.187	13.180	3.200
17	6.58	10.13	11.58	11.75	34.505	8.833	13.940	2.660
18	6.33	8.73	9.50	9.55	31.08	10.027	13.191	2.550
19	6.08	8.48	8.73	8.25	31.275	8.460	10.193	2.900
20	6.88	9.30	10.53	10.90	26.949	6.740	14.114	3.073
21	7.40	10.33	11.63	11.50	37.384	10.033	18.938	4.707
22	7.30	9.00	9.33	9.20	30.091	9.860	9.395	2.470
23	6.30	8.83	10.03	10.00	26.403	8.753	11.123	2.927
24	6.85	10.45	11.35	11.25	36.065	13.533	19.376	5.833
25	6.68	9.60	10.95	11.10	33.948	8.963	13.593	2.808
26	6.35	8.65	9.80	10.15	28.358	8.460	10.587	2.640
27	6.50	9.35	10.13	10.10	37.424	12.033	18.846	4.427
28	8.10	10.60	12.10	11.70	37.337	11.980	17.086	5.457
29	6.88	10.75	11.18	11.00	39.898	9.547	12.632	2.693
30	6.98	10.45	11.48	11.30	38.389	10.567	15.075	4.583

TABLE 24 (Continued)

num	MF40 kg/cm	p40 kg	Avg F. kg	Avg R. Rdiv	CFN50 Hz	EB85-160
1	4.046	1.300	1.583	8.333	63.48	0.351
2	7.064	2.333	2.667	5.433	61.04	0.356
3	5.011	1.417	2.133	7.217	69.58	0.410
4	3.138	1.067	1.327	10.750	69.58	0.494
5	3.522	1.560	1.983	6.733	64.70	0.426
6	2.665	0.957	1.067	10.537	74.46	0.507
7	3.120	1.233	1.420	10.117	79.35	0.511
8	5.207	1.640	1.730	8.777	70.80	0.473
9	2.540	0.870	1.017	10.627	74.46	0.474
10	4.118	1.370	1.770	8.377	67.14	0.414
11	4.507	1.403	1.570	9.227	68.36	0.422
12	3.947	1.217	1.230	10.367	74.46	0.526
13	3.424	1.093	1.207	10.173	67.14	0.380
14	7.464	1.457	1.623	11.643	73.24	0.525
15	5.484	1.050	1.273	11.360	75.68	0.509
16	4.921	1.460	1.337	10.867	78.13	0.526
17	7.816	1.200	1.500	11.153	72.02	0.496
18	5.739	1.083	1.610	9.260	70.80	0.446
19	5.541	1.553	2.427	8.487	72.02	0.473
20	5.634	1.073	1.437	10.243	73.24	0.525
21	5.535	1.107	1.730	11.153	89.11	0.591
22	5.028	1.217	1.830	9.177	72.02	0.455
23	6.049	1.500	1.863	9.620	73.24	0.480
24	9.827	1.853	1.713	11.017	87.89	0.550
25	4.893	1.007	1.647	10.550	79.35	0.584
26	3.482	0.983	1.820	9.533	74.46	0.517
27	4.352	0.787	1.310	9.860	87.89	0.522
28	6.188	1.317	1.778	11.467	90.33	0.522
29	4.428	1.057	1.373	10.977	84.23	0.536
30	6.367	1.107	1.487	11.077	83.01	0.539

TABLE 25

CORRELATION OF DATA FOR SEEDLESS CULTIVAR

	CFN50	EB85-160	Avg F.	Avg R.	Wt	MF8
CFN50	1.0000					
EB85-160	0.8225	1.0000				
Avg F.	-0.2861	-0.3478	1.0000			
Avg R.	0.6810	0.7577	-0.7031	1.0000		
Wt	0.7829	0.6960	-0.2694	0.6530	1.0000	
MF8	0.7537	0.7291	-0.0526	0.5479	0.8237	1.0000
p8	0.6271	0.4034	0.1558	-0.1836	0.5714	0.6630
MF20	0.6861	0.6022	-0.4010	0.5095	0.4991	0.3456
p20	0.3231	0.2258	-0.2616	0.1743	-0.1781	-0.0907
MF40	0.2484	0.1972	0.4028	0.1253	0.3207	0.4868
p40	-0.3368	-0.3940	0.7321	-0.5642	-0.2589	-0.2261
PRT	-0.1192	-0.0274	0.2447	-0.0581	0.1037	0.0449
PT1	-0.3912	-0.3718	0.8039	-0.6869	-0.3037	-0.1690
PT2	-0.2165	-0.3296	0.9150	-0.6320	-0.2057	-0.1054
PH	-0.2018	-0.2665	0.9185	-0.5887	-0.2227	-0.0457
SRT	0.6853	0.6712	-0.5425	0.8560	0.6670	0.5481
ST1	0.7201	0.7417	-0.6600	0.9724	0.7185	0.5955
ST2	0.6853	0.7655	-0.6945	0.9966	0.6557	0.5412
SH	0.6216	0.7338	-0.7172	0.9862	0.5760	0.4973

	p8	MF20	p20	MF40	p40	PRT
p8	1.0000					
MF20	0.4743	1.0000				
p20	0.2019	0.7778	1.0000			
MF40	0.5296	0.1331	-0.0668	1.0000		
p40	0.0867	-0.2730	-0.0013	0.5281	1.0000	
PRT	0.2925	0.2042	0.2745	0.3065	0.3154	1.0000
PT1	0.0875	-0.3721	-0.1654	0.3475	0.7608	0.3162
PT2	0.1230	-0.3638	-0.2459	0.4010	0.7294	0.3130
PH	0.1732	-0.3440	-0.2596	0.3422	0.5548	0.1195
SRT	0.1851	0.4454	0.1368	0.0665	-0.5176	-0.0183
ST1	0.2340	0.5247	0.1948	0.1528	-0.5287	-0.0044
ST2	0.2036	0.5330	0.2004	0.1259	-0.5537	-0.0331
SH	0.1196	0.4566	0.1277	0.0991	-0.5797	-0.1202

TABLE 25 (Continued)

	PT1	PT2	PH	SRT	ST1	ST2	SH
PT1	1.0000						
PT2	0.7818	1.0000					
PH	0.5343	0.4361	1.0000				
SRT	-0.6170	-0.4550	0.4258	1.0000			
ST1	-0.6384	-0.6077	0.5487	0.8754	1.0000		
ST2	-0.6795	-0.6186	0.5837	0.8541	0.9623	1.0000	
SH	-0.7045	-0.6391	0.6013	0.8108	0.9241	0.9817	1.0000

VITA

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