Using radio frequency spectral measurements for determination of corn mechanical damage

by

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For the Major Program

"Praise Be to ALLAH
Lord of the Universe"

To the memory of my father...
To my Mother ...
To Khulood, Nusser, and Mohamad ...
To Stuart and Carl ...

I dedicate this work...

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CHAPTER 1: DIELECTRIC PROPERTIES REVIEW

Introduction

Dielectric properties of a material explain the interaction between the material and the electrical field. Dielectrics principles have been used in several applications related to food and agriculture, ranging from microwave ovens which are an essential part of each house, to dielectric moisture sensors based on radio-waves or microwaves, for fast, and accurate moisture measurements of grains. Less wellknown applications include grain drying and insect control in stored grains among several other applications. A brief discussion of the dielectric properties of agricultural materials including some definitions of essential terms, factors affecting dielectrics, and some major applications are presented in this chapter.

Definitions

Complex permittivity (ε): an electric property that describes the interaction of a material with an electric field. It measures the ability of the material to polarize when subjected to an electric field.

Relative complex permittivity (ε_r): the ratio of absolute complex permittivity (ε) to the permittivity of free space given as $\varepsilon_0 = 8.854*10^{-12}$ F/m. Relative complex permittivity is represented by the expression $\varepsilon_r = \varepsilon' - i\varepsilon''$, where ε' denotes the dielectric constant of the material and is associated with the material ability to store electric energy, while ε''denotes the dielectric loss factor which represents the material ability to dissipate electric energy. Dielectric loss factor (ε'') consists of two components: the first one is ionic loss factor which represents the energy losses associated with Ohmic resistance of the material, while the other is related to the energy losses in the dielectric material associated with the relaxation mechanisms. The effective dielectric loss factor is therefore given as the sum of the two components:

$$\varepsilon''_T = \varepsilon'' + \sigma/(\omega\varepsilon_0) \tag{1.1}$$

AC conductivity (σ): the ability of the material to conduct electricity which is given as: $\sigma = \omega\, \varepsilon_0\, \varepsilon''$ (S/m), where ω is the angular frequency $\omega = 2\,\pi\, f$, and f is the electric field frequency in Hz.

Dipole moment: charge distribution imbalance that results from electron rearrangement when atoms combine to form molecules. These moments are arranged in a random manner in the absence of electric field and are not polarized, however, when subjected to an electric field the molecules align themselves to the electric field causing orientation polarization.

Relaxation time (τ): time required for the dipoles to return to equilibrium.

Throughout this discussion, complex permittivity (ε) is used to express complex relative permittivity (ε_r).

Theory

The time-harmonic form of Maxwell's equations can be used to derive the dielectric properties of materials. These equations are given as (Nelson, 1991):

$$\nabla \times \mathbf{E} = -j\,\omega\,\mathbf{B} \tag{1.2}$$

$$\nabla \times \mathbf{H} = \mathbf{J} + j\,\omega\,\mathbf{D} \tag{1.3}$$

$$\nabla \cdot \mathbf{D} = \rho \tag{1.4}$$

$$\nabla \cdot \mathbf{B} = 0 \tag{1.5}$$

Where **E** is the phasor electric field intensity, **B** is the phasor magnetic flux density, **H** is the phasor magnetic field intensity, **J** is the phasor volume density of free current, **D** is the phasor electric flux density, ω is the angular frequency, and ρ is the volume charge density of free charges. The constitutive equations are defined as:

$$\mathbf{D} = \varepsilon\,\mathbf{E} \tag{1.6}$$

$$\mathbf{B} = \mu\,\mathbf{H} \tag{1.7}$$

$$\mathbf{J} = \sigma\,\mathbf{E} \tag{1.8}$$

Where ε is the absolute permittivity, μ is the absolute permeability, and σ is the medium conductivity. Another way to express equations 1.6 and 1.7 is:

$$\mathbf{D} = \varepsilon_0\,\varepsilon_r\,\mathbf{E} \tag{1.9}$$

$$\mathbf{B} = \mu_0\,\mu_r\,\mathbf{H} \tag{1.10}$$

Where ε_r is the relative complex permittivity, ε_0 is the absolute permittivity of the free space, $\varepsilon_0 = 8.854 \times 10^{-12}$ F/m, μ_r is the complex relative permeability, and μ_0 is the complex relative permeability of the free space, $\mu_0 = 4\pi \times 10^{-7}$ H/m. Permittivity and permeability of free space can be related to each other using the speed of light c, as followes:

$$c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}} \tag{1.11}$$

The permeability of most agricultural materials is similar to the permeability of the free space and therefore the complex relative permeability is equal to unity. The relative permittivity is often used to express the permittivity, which is a complex quantity consisted of real part (ε'_r) and imaginary part (ε''_r), where ε'_r and ε''_r are relative dielectric constant and relative loss factor respectively.

To obtain the total current flowing through a dielectric material, equation (1.6) and equation (1.8) can be substituted to equation (1.3), this results in:

$$\nabla \times \mathbf{H} = \sigma\, \mathbf{E} + j\, \omega\varepsilon\, \mathbf{E} = (\sigma + j\, \omega\varepsilon)\, \mathbf{E} \tag{1.12}$$

Then by substituting the expression for complex permittivity of equation (1.12):

$$\nabla \times \mathbf{H} = [\sigma + j\, \omega(\varepsilon' - j\varepsilon'')\,]\, \mathbf{E} \tag{1.13}$$

rearranging and using the notation $\varepsilon_r = \varepsilon / \varepsilon_0$:

$$\nabla \times \mathbf{H} = j\omega\varepsilon_0 \left(\varepsilon_r' - j\left(\frac{\sigma}{\omega\varepsilon_0} + \varepsilon_r'' \right) \right) \mathbf{E} \tag{1.14}$$

Loss tangent (tan δ), which is defined as the ratio of the imaginary part to the real part of the total displacement current described in equation (1.15) is often used to measure the power loss in low-loss mediums and is defined as:

$$\tan\delta = \frac{\varepsilon''_r + \dfrac{\sigma}{\omega\,\varepsilon_0}}{\varepsilon'_r} \tag{1.15}$$

Wet grain has water which is a polar molecule that aligns it self with the applied electric field, this aligning process is possible at the lower frequencies where the electric field alternates slowly. However, when frequency increases it becomes more difficult for the bound charges to move and align themselves to the field until it completely loses track of the electric field. At this point, energy will be needed to stop momentum and reverse the molecule and this causes intermolecular friction that results in heat dissipation. This accounts for the ε''_r term in equation (1.15). The other type of loss is associated with the movement of the free charges, which occurs when current flows by electric conductivity, this type is represented by the term $(\sigma/(\omega\varepsilon_0))$ in equation (1.15). The combination of dielectric loss and ohmic loss represents the effective dielectric loss factor ($\varepsilon''_r + (\sigma/(\omega\varepsilon_0))$). It is important to notice that the second term will be more dominant at the lower frequencies and disappears as frequency increases. The two terms will be pooled together and used as the effective dielectric loss factor since attempt to separate them for heterogeneous materials (such as wet grain) have not been successful.

Lawrence (1998) reported the contribution to dielectric loss in heterogeneous aqueous systems over frequency range from dc to optical region as shown in figure 1.1. This included ionic conductivity, surface conductivity, charged double layer effects, free and bound water relaxation, ice relaxation, and Maxwell-Wagner effect. For the frequency range from dc to 10 MHz the main effects include: ionic conductivity, charged double layer, Maxwell-Wagner effect (dielectric dispersion that occurs when conducting particles exist in suspension in

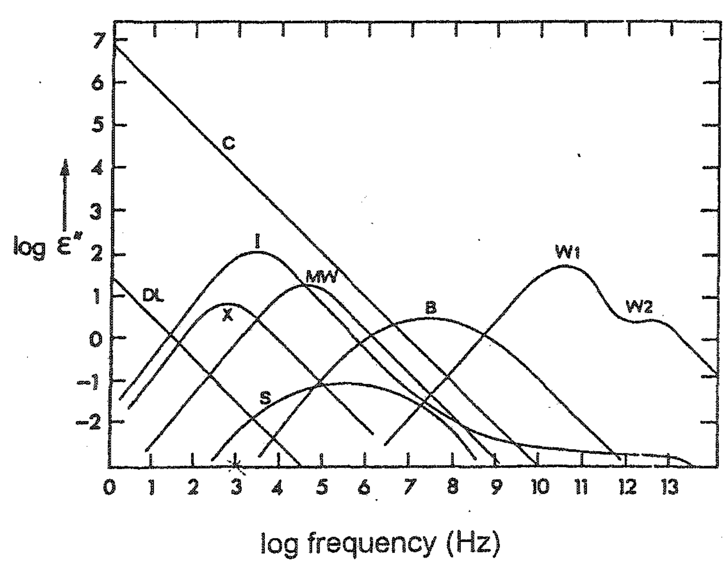

Figure 1.1 Dielectric dispersions of moist materials. C-ionic conductivity, DL- charged double layer, X-crystal water relaxation, I-ice relaxation, MW- Maxwell-Wagner effects, S-Surface conductivity, B-bound water relaxation, W1-principle relaxation of free water, and W2- second relaxation of free water (Lawrence 1998).

a non-conducting dielectric medium), surface conductivity, and bound water relaxation. The effect of crystal water relaxation and ice relaxation do not apply to this research which was conducted under room temperature around 25 ^{0}C.

Factors affecting dielectric properties

Frequency

In most dielectric materials including agricultural material, dielectric properties vary considerably with frequency of the electric field. This dependence is primarily due to the polarization arising from the orientation of molecules which have permanent dipole moments with the applied electric field. A mathematical expression was developed by Debye, 1929 (Nelson 1991) to explain this process for pure polar materials, this expression is given as:

$$\varepsilon_r = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + i\omega\tau} \tag{1.16}$$

Since $\varepsilon_r = \varepsilon_r' - j\varepsilon_r''$

$$\varepsilon_r' = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + \omega^2\tau^2} \tag{1.17}$$

$$\varepsilon_r'' = \frac{(\varepsilon_s - \varepsilon_\infty)\omega\tau}{1 + \omega^2\tau^2} \tag{1.18}$$

where ε_∞ represents the permittivity at very high frequency, and molecular orientation does not have enough time to contribute to polarization, ε_s is the static permittivity or DC permittivity (at zero frequency); τ is the relaxation time which is the time in seconds needed by the dipoles to return to their random orientation after the electric field is removed, and ω is the angular frequency of the electric field in rad/s. For free water, $\varepsilon_s = 80.2$, $f_r = 17.11$ GHz

@ 20 °C, and $\varepsilon_\infty = 4.3$ (temperature independent), where $f_r = (2\pi\tau)^{-1}$. It can be shown using equation (1.18), that the dielectric losses at high frequencies and at DC (zero) frequency are essentially zero for pure polar materials. However, at intermediate frequencies the permittivity undergoes dispersion and dielectric loss occurs with a peak loss at the relaxation frequency, $\omega = 1/\tau$.

Equation (1.16) does not represent most of the dielectric materials, which essentially have more than one relaxation time. The Cole – Cole equation is the one, which has been used to account for multiple relaxation times Nelson (1991):

$$\varepsilon_r = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + (i\omega\tau)^{1-\alpha}} \tag{1.19}$$

Where α devotes the spread of relaxation time, and is an empirical parameter that takes a value between 0 and 1. Free liquid water is an example of a polar dielectric with $\alpha = 0.012$. In agricultural materials. Water is usually bound or adsorbed to other molecules in material capillaries and therefore dielectric relaxation of this bound water occurs at lower frequencies than free water. Other effects exist with heterogeneous systems (such as moist grain), which makes prediction of dielectric properties using Debye equation unsuitable. These effects include ionic conductivity, charged double layer, Maxwell-Wagner effect, free and bound water relaxation, and other effects.

Measurements of dielectric properties for corn, wheat, oats, barely, and several other grains and seeds at low and high frequencies showed that the dielectric constants had considerably higher values at audio-frequencies (250 Hz to 20 kHz) than at radio-frequencies (1 to 50 MHz) at comparable moisture levels. The dielectric constant was found to either decrease or remain constant with frequency increase, Stetson and Nelson (1972; Nelson, (1952). The dielectric loss factor either increased or decreased with frequency increase, depending on moisture content and frequency range (Nelson, 1965).

Generally, studies showed that dielectric constant decreased with frequency increase at the same moisture content, temperature, and bulk density. The dielectric loss factor showed an irregular behavior, which can be attributed to the dielectric relaxation and dispersion phenomena.

Moisture content and Bulk density

It is convenient to discuss the effect of both moisture content and bulk density on dielectric properties of grain and agricultural materials since they are related to each other. An increase in the amount of a wet material (increase in bulk density) will lead to an increase in the amount of water perceived by the electric field and therefore the resulting measured dielectric properties. Water has a dielectric constant about 80 (at room temperature) while grain dry matter has a dielectric constant about 3, this variation provides the foundation for developing sensitive moisture measurements using the dielectric properties.

The amount of material per volume (density), also, has an important effect on the dielectric properties, this is due to the interaction of the material with electromagnetic field. In agricultural materials like grains and seeds, an understanding of the relationship between dielectric properties of solid – air mixture might be useful in understanding the dielectric properties of the solid material. Dielectric mixture equations of dielectric properties were developed to calculate the dielectric properties of solid material from properties of air-particle mixtures made up of air and particle material. Nelson (1983) reported a linear function of bulk density using the complex permittivity of particulate materials such as: wheat, whole-wheat flour and pulverized coal.

Nelson, et al, (1991) found that the best prediction equation for air-particle mixture was based on the refractive index and Landau, and Lifshitz mixture equation, which estimates the dielectric constant of an air-particle mixture at a certain density given a measured dielectric constant at a reference density. This expression is given as:

$$\varepsilon_{r2}' = \left[\frac{\left((\varepsilon'_{r1})^{1/3} - 1\right)}{\rho_1}\rho_2 + 1\right]^3 \tag{1.20}$$

where ε'_{r1} is the measured dielectric constant at bulk density (ρ_1) and ε'_{r2} is the unknown dielectric constant with bulk density ρ_2. Nelson (1978, 1979b) found that for corn with moisture content range from 10-35 percent, the relationship between dielectric constant (ε'_r) and bulk density was linear. He also found an increase in the slope of dielectric constant versus bulk density with an increase in moisture content. Jones et al. (1978) compared dielectric properties of settled and unsettled grain samples and reported a large variation in dielectric constant with bulk density variation at high moisture contents for corn, wheat and soybeans. Kraszewski, et al. (1977) found that settling the grain samples resulted in a higher increase in dielectric loss factor compared to dielectric constant, which indicated that dielectric loss factor could be useful for correcting dielectric constant for density variation. They also suggested that measuring attenuation and phase shift at microwave frequencies could be useful for correcting for bulk density.

Temperature

Dielectric properties of agricultural materials are temperature dependent. This dependence is related to dielectric relaxation processes and excitation frequencies used. Generally, relaxation time decreases as temperature increases. The dielectric constant will increase with increase in temperature. The dielectric loss factor will either increase or decrease with temperature increase depending on the relationship between operating frequency and relaxation frequency, this behavior can be explained by noting that the dielectric loss factor peak will shift to higher frequencies as temperature increases. Nelson (1965) found that both dielectric constant and loss factor varied linearly with temperature at 40 MHz. Knipper (1959) reported that dielectric loss factor was linearly related to temperature at 54 kHz and 9.6 MHz, and that dielectric constant was positively correlated with temperature while dielectric loss factor either increased or decreased depending on moisture content and frequency. Jones, et. al (1978), reported a positive temperature coefficient of dielectric constant for wheat, soybeans, and corn at 30 MHz at 2 ^{0}C and 40 ^{0}C. Nelson (1979) found that at the same moisture content, bulk density, and frequency, the dielectric constant increased with temperature increase.

Trabelsi, et al.(1998) reported that molecular polarization is the predominant type of polarization in the microwave frequency range (above 1 GHz). They also reported that temperature affects the energetic status of water molecule and their ability to rotate with the applied electric field which also affects complex permittivity. They stated that both bulk density and temperature are water related effects and the effect of each of them on complex permittivity is interrelated.

Other factors

Nelson (1980) reported that different grain lots may result in variation in bulk density. He found that variation due to physical characteristics (like kernel size and shape as well as chemical composition variation) could play an important role in dielectric properties along with density variation. He indicated that kernel densities could be correlated to bulk density over a wide range of moisture content. Other studies, reported that dimensions of kernels had an effect on dielectric properties when they represent a considerable fraction of the electrode spacing (Jones et al., 1978; and Nelson 1979). At microwave frequencies where wavelengths may not be long in proportion to kernel dimensions, dielectric measurements could be less accurate for particulate materials.

The effect of sorption-desorption cycles of grain on measured dielectric properties was studied by Soderholm (1961). He found that at a frequency range from 1 to 50 MHz, the dielectric properties of grain at 12 % moisture content for grain that was dried then re-wetted grain varied less than 5 % from naturally dried corn after harvest. Other studies conducted by Stetson and Nelson (1972) found that no difference existed between sorption-desorption properties of hard red winter wheat at audio frequencies (250 Hz to 20 kHz) with moisture contents between 6.6 and 19.5 percent.

Nelson (1981) indicated that foreign materials, particles of broken kernels, and insects infestation could affect dielectric properties of grain. He also reported that spoilage of high moisture corn could affect dielectric properties specially at lower frequencies where the contribution of ionic conductivity is higher.

The effect of chemical composition on dielectric properties was also investigated. Nelson and Stetson (1976) studied the effect of chemical composition of wheat on dielectric properties. They did not observe any significant relationship between dielectric properties and protein, fat, ash content of several wheat lots, and suggested that any variation due to composition were masked by other factors.

Grain types and varieties effects on dielectric properties were investigated by Nelson (1978b). He reported that variation in dielectric properties among different types from the same species could be significant. He also found a variation of 5 to 18 % in the measured dielectric properties of flint and floury-endosperm as compared to yellow-dent shelled corn. Flint corn had a higher dielectric constant while floury corn had a lower dielectric constant than yellow-dent shelled corn.

Applications of dielectrics in agriculture

Moisture content and bulk density measurements

Most of the work on dielectric measurements was concerned with developing moisture measurements rather than developing bulk density measurements. However, the dependence of moisture content measurements on bulk density created a need for considering bulk density effect carefully while developing moisture content sensors. Studies have considered the effect of both factors on dielectric properties and two different approaches have been used. The first one was based on using density-independent functions for measuring moisture content of grain. In an attempt to develop an on-line moisture sensor that can be used with flowing grain, this technique investigated certain density – independent functions that did not show significant changes in moisture measurements as bulk density changes. However, these functions do not provide completely density-independent moisture measurements, although minimize the dependence of moisture measurements on bulk density (Lawrence et al. 1993; Berbert, and Stenning 1996a; lawrence 1997). The second approach was based on using multi-frequency measurements for instantaneous prediction of grain physical properties, including moisture content, bulk density, and temperature.

McFarlane (1987) reported using two-frequency dielectric constant measurements at 0.1 and 10 MHz to develop an expression for predicting moisture content by eliminating the bulk density from both measurements. Lawrence et al. (1993) developed a two–frequency density-independent function to predict moisture content for hard red winter wheat. The two frequencies used were 1 and 10 MHz. They demonstrated the ability to predict moisture contents values with a standard deviation of 0.5 percentage point moisture at moisture content between 11 to 22 %, and a density range between 650 and 850 kg/m^3. The prediction equation was found to work better for moisture contents above 14 percent (w.b.). Stenning and Berbert (1993) used dielectric constant measurements of hard red winter wheat at 0.3 and 8 MHz to predict moisture content between 12.1 and 18 %. They developed a regression between the dielectric constant of the wheat samples at 0.3 and 8 MHz for both moisture content and bulk density. These two equations were used to eliminate bulk density and develop a density independent moisture measurement. Their equation predicted moisture content with an average error of 0.8 percent. Berbert and Stenning (1996) evaluated a density–independent dielectric function that is commonly used for measuring moisture content of hard red winter wheat in the range between 11.5 % to 21.5 %. They found that the single frequency density-independent function was able to predict moisture content with a standard error of calibration of 0.5 percent.

Kraszewski et al. (1998) found that a density independent function described by the ratio of attenuation to phase shift was independent of layer thickness and bulk density for wheat. They reported that both attenuation and phase shift measured at 16.8 GHz were density dependant, therefore their ratio was density-independent. They used this density independent function to measure moisture content of corn in the range 10 to 19 percent with a temperature range from –1 to 42 $^{\circ}$C. Nelson (1979) used bulk density, kernel density, moisture content and temperature to provide a reasonably good estimate of dielectric constant of shelled corn at 20, 300, and 2450 MHz. He developed a relationship between kernel density and moisture content and used that to predict the dielectric constant at 2450 MHz using moisture content, bulk density and temperature only. Trabelsi, et al., (1999) used the density-normalized effective relative complex permittivity ε''/ρ_b and ε'/ρ_b to identify the dielectric material and provide a calibration equation for determining the physical properties of that material from permittivity measurements. They used the relation between ε''/ρ_b and ε'/ρ_b to estimate the bulk density of corn and wheat at 13.3 and 18 GHz, independent of moisture content and temperature. A similar function was used to predict moisture content independent of composition, geometry, or dimensions of the sample particles.

Three different single kernel moisture measurement systems were also developed from measurements of kernel dielectric properties. The first system was based on the dc conductance of the corn kernel measured as it passes between two crushing rollers (Nelson et al., 1989). In the second system, the corn kernel is placed between two plates of a parallel plate capacitor and radio - frequency measurements of dielectric properties obtained and for determination of moisture content (Kandala, et al., 1987). In the third system a microwave cavity resonator perturbation is used to obtain kernel moisture (Kraszewski et al., 1990). The first method is a destructive method while the other two methods are nondestructive. Nevertheless, the first system found more acceptance in industry and has been developed into a commercial system.

Heating and drying

Dielectric heating results from intermolecular friction between water and other molecules in the material matrix. The friction is induced by the oscillatory behavior of the polar water molecules when they attempt to align themselves with the applied electric field, resulting in heat dissipation. Depending on the frequency range, heating is divided to radiowave heating (RF), or microwave heating (MF). Radiowave heating was developed first then followed by microwave heating (Brown et al., 1947). Applications of dielectric heating in agriculture included drying of grain and other products, seed treatments to control insect infestations, improve germination, heating, pasteurization, and sterilization. Nelson, et al. (1985) studied the effectiveness of RF on improving germination of selected plant seeds.

The effect of RF exposure on controlling the insect infestation of stored grain has been studied (Nelson et al., 1960; Nelson et al., 1966; Nelson 1976). However, RF control of insect in stored grain has not become practical since chemical treatments were more cost effective, Nelson, (1991).

Product quality measurements

Nelson (1980) investigated the possibility of using dielectric properties for predicting maturity in peach, and detection of 'hard core' condition in sweet potatoes. He found that single frequency measurements were not useful. However, he suggested that dielectric properties measured over a wider frequency range might help developing nondestructive techniques for measuring agricultural products quality.

CHAPTER 2: GRAIN MECHANICAL DAMAGE REVIEW

Introduction

Corn is one of the major crops in the United States, with 31 Million ha harvested in 2000 producing over 253 million metric tons of corn, (USDA, 2001). Without modern agricultural machinery, such large amounts of grain could not be produced. At the same time introduction of mechanical harvesting resulted in a greater grain mechanical damage from harvesting and subsequent handling operations. Mechanical damage received a lot of attention during the past five decades. However, there has been no agreement among researchers and grain industry sectors on the definition of grain mechanical damage and each party has set its own definition. For example, the USDA Grain Inspection Service, which provides the official grading for grain in the United States, uses BCFM (broken kernel and foreign materials) as an indication of mechanical damage for corn. This includes any foreign materials other than corn in addition to the portion of corn that passes through a 4.76 mm round-hole sieve (USDA 1999). This represents a small portion of the total mechanical damage that actually results from mechanical harvesting (Chowdhury and Buckele, 1976a; Kalbasi-Ashtari et al. 1979). On the other hand, the seed industry enforces more rigorous methods for evaluating seeds for visible, invisible, and hairline cracks which might affect their ability to grow and develop reasonably healthy seedlings. The mechanical damage to be investigated here includes any visual damage inflicted upon the corn kernel by means of mechanical forces due to harvesting and any subsequent operation that falls into this category. It would be useful to review relevant literature on mechanical damage first.

Reports on mechanical damage from combine harvesting varied widely in the literature. Early reports showed that corn mechanical damage, which includes visible and hidden damage varied between 16.5 and 40 percent (Mahmoud and Buchele, 1975; Chowdhury and Buchele, 1976a; Kalbasi-Ashtari et al., 1979). Paulsen and Nave (1980) reported that mechanical damage below 10 percent was considered very good. They defined damage as visual cracks or chops to the corn kernel. More recent studies showed that visual mechanical damage was as low as 5 percent at optimal combine settings (Quick, 2001). Other reports showed that mechanical damage ranged between 6 percent for corn harvested at 13 and 18 percent moisture content and 9 percent for corn harvested at 25 percent moisture content (Melvin, 2001). He defined mechanical damage as any ruptures or cracks in the seed coat. Several definitions were developed for mechanical damage by different researchers. Mechanical damage was defined to include all categories of physically chopped or cracked corn kernels (Koehler, 1957; Brass, 1970). ASAE defined mechanical damage as the damage caused by mechanical harvesting and classified it into visual and hidden damage (ASAE 1999). Chowdhury and Buchele (1975) categorized mechanical damage into four groups: minor, major, severe, and fines.

Mechanical damage of grain could adversely affect its quality. Paulsen and Nave (1980) reported that mechanical damage results in easier fungal invasion, more insect manifestation, and increased breakage during subsequent handling. Mechanically harvested corn is more expensive to dry. Saul and Steel (1966) reported that energy costs for drying mechanically damaged corn increased by six to seven times over that required for drying hand-shelled corn, because damaged corn needed faster drying rates to prevent deterioration. Deterioration is usually associated with mold growth, especially at higher moistures and temperatures. Molds usually grow on grains and produce mycotoxins, which are secondary metabolites of the mold. A common mycotoxin encountered in grains is aflatoxin, which is the metabolite of the fungus *Asperagillus Flavus*. This mold causes serious problems in the grain industry due to its high toxicity for both humans and livestock. Kalbasi-Ashtari et al. (1979) reported that damaged and undamaged portions of mechanically-shelled corn had a higher deterioration rate than hand shelled corn by a factor of 2 and 3 times, respectively. Ng et al. (1998) studied the effect of mechanical damage on corn storability as determined by carbon dioxide production and dry matter loss. They found that allowable storage time (AST) decreased as mechanical damage increased from 0 to 40 percent and remained constant from 40 to 50 percent. Grain processing quality is also adversely affected by mechanical damage. Freeman (1970) reported that such corn resulted in lower oil recovery, poor milling ability, lower content of gluten pigments, and lower starch viscosity. Almeida-Dominguez et al. (1998) studied the effect of corn mechanical damage (0 to 30 percent) on the performance of alkaline cooking of corn into tortillas. They found that corn with high mechanical damage was susceptible to overcooking, more difficult to handle during processing, and had more nutrient loss compared to undamaged corn. The seed industry is concerned about seed viability, germination, vigor, and growth rate which are greatly affected by seed injuries, which leads to a great deal of yield losses. (Gomez and Andrew, 1971).

In order to minimize the problems associated with grain mechanical damage, it's important to develop an accurate, fast technique that can be used to evaluate mechanical damage in grain. The grading system used by USDA Federal Grain Inspection Service is the system used officially in the grain trade. Nevertheless, this system accounts for a small portion of actual mechanical damage. In corn grading, it offers provisions for evaluating the broken corn and foreign material (BCFM) portion only. This grading system represents any non corn material in addition to the corn fraction that passes through a 4.76 mm (12/64 in) round-hole sieve. Kalbasi-Ashtari et al. (1979) reported that the actual mechanical damage of machine shelled corn was about 16.5 percent, while fines and foreign material were 1.1 percent of the corn sample, based on the procedure explained by Chowdhury and Buchele (1975) to categorize damage into minor, major, severe, and fines proportions. Similar studies by Chowdhury and Buckele (1976a) reported an average BCFM of 0.77 percent compared to 40.37 percent total mechanical damage using a laboratory corn sheller. Unfortunately, there is a wide variation among the measurements of mechanical damage in literature due to the fact that there has been no universal definition for mechanical damage. The procedure used for damage evaluation and the human subjectivity has affected these measurements and made them inconsistent from one researcher to another. Nevertheless, it is quite obvious from literature that actual mechanical damage is far greater than the portion obtained from the USDA grading system. The farmer is neither rewarded for producing a premium quality grain, nor penalized for the lower quality grain, as long as the grade is not affected under the current official grading system. Knowing that grains at the same grade level could widely differ in terms of the mechanical damage proportions, it might be useful to adopt a more effective system, which rewards the farmer for a better quality grain. However, such a system should be reliable and easy to implement before it could be effectively adopted.

Causes of grain mechanical damage

The causes of grain mechanical damage could be divided into two broad categories. The first category includes those factors associated with crop physical conditions such as kernel moisture content, detachment force, and others. The second category includes those factors associated with harvesting operation itself such as cylinder speed, cylinder–concave clearance and others. The two categories will be discussed briefly.

Damage associated with crop physical conditions

These include factors that are inherent to the grain itself, like moisture content, variety, kernel detachment force, and others. Mechanical damage was reported to increase substantially with increase in moisture content (Morrison, 1955). Hall and Johnson (1970) reported that the minimum amount of fines was produced when corn was shelled at moisture content between 20 and 24 percent in a laboratory combine cylinder. Buchele (1976) found a positive logarithmic relationship between kernel damage and moisture content between 15 and 38 percent. Melvin (2001) found that mechanical damage increased with moisture content increase. He found that mechanical damage at 25 percent moisture content was about 9 percent compared to 6 percent mechanical damage at 13 and 18 percent moisture content. Seghal and Brown (1965) observed more kernel injury and cob splitting in the case of hard shelling cobs. Waelti (1967) showed that kernel detachment force, kernel and cob strength, affect corn mechanical damage. Mahmoud and Kline (1972) observed a high correlation between pericarp thickness and hidden damage of corn kernels.

Damage associated with harvesting operation.

These include the operating conditions at harvest like cylinder speed, cylinder-concave clearance, efficiency of shelling operation, operator skills, and others. Ayres et al. (1972) observed that higher than recommended cylinder rpm speed and varieties that did not shell easily resulted in a damage higher than average. Mahmoud and Buchele (1975) reported an increase in mechanical damage from 15 percent at the concave inlet to 45 percent damage past the concave extension. They concluded that this was caused by the repetitive striking of corn kernel by the cylinder raspbar as the kernel travels along the concave. They considered all physically damage kernels as mechanical damage. Koehler (1957) showed that corn mechanical damage caused by a cylinder sheller was estimated as 14.3 percent crown injury, 28 percent embryo injury, 13.4 percent other pericarp injuries, 6.6 percent tip-cap broken off, and 3.9 percent cracked kernels. Kline (1972) reported that combine-shelled corn had over 5 percent visible damage compared to 40.5 percent internal damage indicated by fast green dye. More recent measurements obtained by Quick (2001) showed that combine visual mechanical damage was as low as 5 percent at optimal combine running conditions. He used a John Deere STS 9650 combine with a cylinder speed of 360 rpm and a ground speed ranging from 3 to 5 mph.

Evaluating grain mechanical damage

Mechanical damage causes substantial problems in the grain industry. The problems include higher drying and storage costs, lower profit and quality. However, the severity of the problem depends on the intended use of the grain. If the grain is intended to be used for livestock feed shortly after production, mechanical damage does not appear to be a major concern. On the other hand, grain intended for long term storage, shipping, seed production, or milling is adversely affected by grain mechanical damage.

Kaminski (1968) summarized the factors related to the effect of grain mechanical damage on the value of the grains as related to their intended use as follows:

1. Numerical grades to the farmer: USDA- grain inspection service, uses a grading system to evaluate the grain quality and therefore it's price. The farmers are interested

in getting the highest price for their grain.

2. Seed viability: grain industry is interested in the ability of the seeds to emerge into an acceptable seedling.
3. Handling and transportation: grain handling sectors are interested in the ability of grain to resist cracks and damage during handling and transportation
4. Storability: effect of grain mechanical damage on the magnitude of deterioration during storage is of interest.

Techniques have been developed to evaluate the quality aspects of grain including mechanical damage. Those systems have their own specific applications as well as advantages and disadvantages. A brief discussion of those important techniques will be introduced.

Official grain standard method (USDA grain standard):

Federal grain standards for corn were developed and implemented in July 1914. These standards evaluate several parameters including corn damage, moisture content, foreign material, cracked corn, and another eleven general rules describing identity, condition, and color of corn. At that time, test weight was not one of the parameters tested. The next development was in 1916 when the United States Grain Standard Act was passed with minor changes made thereafter. Uhring (1968) reported the characteristics that determine the grades, which include:

a. Classes or colors, such as yellow, white, or mixed corn.
b. Factors that determine the numerical grade, such as test weight per bushel, moisture content, foreign material, damaged kernels, and the presence of other impurities from different grain classes or types.

c. General condition factors. These include live weevils, sour, bleached, garlic, smut kernels and other similar conditions.

Presently, the latest USDA grain grading standards (USDA 1999) are used for corn grading. The standards consist of six numerical grades from one to six. Grade no. 1 represents the highest quality and grade no. 5 represents the lowest classified quality, while grade no. 6 is known as the sample grade where one or more of the grading factors is lower than the minimum requirement for a numerical grade. Table 2.1 has an explanation of sample grain and standards basis for numerical grades.

This grading system accounts for the broken corn and foreign material (BCFM), which readily passes through a 4.76 mm (12/64 in round-hole sieve only) in addition to any non corn materials. This system, however, does not account for other types of mechanical damage, which also have a considerable effect on grain quality. Test weight, as criteria for evaluating corn quality has not been proven to be efficient. Hall and Hill (1973) reported that moisture content, corn variety, drying temperature, and kernel damage have affected test weight. This system penalizes the producer for lower quality corn but it does not provide an incentive for higher quality corn, which is not accounted for by numerical grades. The USDA grain grading standards are not widely approved by different grain industry sectors; therefore, methodologies were developed for more specific uses of grain in various grain and seed industries.

Visual inspection methods:

Visual inspection is widely used in grain grading. The main advantage of this system is its simplicity and acceptability. The disadvantages include inefficiency and the role of

Table 2.1. USDA grade requirements for corn.

Grade	Min. test weight (lbs/Bu)	Maximum limits % Heat damaged kernels	Total damaged § kernels	Broken corn and foreign material
U.S. No. 1	56.0	0.1	3.0	2.0
U.S. No. 2	54.0	0.2	5.0	3.0
U.S. No. 3	52.0	0.5	7.0	4.0
U.S. No. 4	49.0	1.0	10.0	5.0
U.S. No. 5	46.0	3.0	15.0	7.0
U.S. Sample grade.				

U.S. Sample grade is corn that:
(a) Does not meet the requirements for the grades U.S. Nos. 1,2, 3, 4, or 5; or
(b) Contains stones which have an aggregate weight in excess of 0.1 percent of the sample weight, 2 or more pieces of glass, 3 or more crotalaria seeds (Crotalaria spp.), 2 or more castor beans (Ricinus communis L.), 4 or more particles of an unknown foreign substance(s) or a commonly recognized harmful or toxic substance(s), 8 or more cocklebures (Xanthium spp.) or similar seeds singly or in combination, or animal filth in excess of 0.20 percent in 1,000 grams; or
(c) Has a musty, sour, or commercially objectionable foreign odor; or
(d) Is heating or otherwise of distinctly low quality.

human subjectivity. Two different visual inspection methods are used; quantitative and qualitative. Researchers have used quantitative method to evaluate damage as a percentage of the total sample weight. In quantitative visual inspection method, a 500-g sample of representative corn is randomly drawn from the corn lot, then a 100-g sub-sample is obtained using a Boerner grain divider. Next the sample is sieved using a 4.76 mm (12/64 in) round-hole sieve and the portion that passes through the sieve is weighed. The remaining corn kernels are soaked in a 0.1 percent Fast Green FCF dye for 4 min to facilitate visual

§ see appendix II for more details on the different types of damage kernels.

inspection and the excess dye is washed away using running tap water. Next, kernels are spread out on a paper towel and left to dry for 24 hr. Finally, the kernels are inspected one by one using a magnifying glass. The kernel is considered damaged if it is broken, chipped, cracked, had bruised pericarp or hairline cracks (Chowdhury and Buchele 1976b). Although this method accounts for most of damage types from fines to kernel chops, it gives each damaged kernel the same weight regardless of the degree of damage. Large variation existed when damage was evaluated using this technique. Schmidt et al. (1968) reported that corn sample size, differences between mechanical damage readings obtained from different inspectors for the same corn sample, and differences between repetitive readings made by the same inspector for the same corn sample were found. This indicated that this technique is highly subjective. Koehler (1957) reported that the dye stains the exposed starch of the damaged corn kernel and make it easier to observe the different degrees of damage. Schmidt et al. (1968) observed that FCF dye increased the amount of detected damage but did not improve the precision. In addition, this method stains the kernel tips and silk points on the pericarb, which may cause confusion due to misidentification of a kernel as damaged while it is not.

A more comprehensive visual damage evaluation technique is the qualitative damage evaluation where both percentage and extent of damage are evaluated. The procedure for evaluating damage using this method is similar to the one explained in the quantitative damage section, except that damaged kernels are further classified based on the severity of damage (Chowdhury and Buchele 1976a). The categories of damage classified by this method varied among researchers. Koehler (1957) reported four major categories of mechanical damage, those included kernels with sound pericarp, cracked kernels, kernels with the tip-cap broken off, and kernels with pericarp injury. Other classifications reported by Brass (1970) consisted of severe damage, embryo damage, crown damage, and pericarp damage. Mahmoud and Kline (1972) reported a five-type damage classification. Chowdhury and Buchele (1975) reported five categories of damage using visual inspection of shelled corn, those included whole kernels, minor damage, major damage, severe damage, and finally broken corn and foreign material.

Although visual inspection presented an advantage over USDA official grading system, disagreement among researchers on the definition of the damage classes and the subjectivity of the technique represent a major drawback of this method.

Seed germination tests methods:

Seed germination tests are commonly used by seed industry to evaluate seed quality for germination. Those techniques are more tailored toward specific needs of the seed industry and are usually slow. Copeland and McDonald (1995) provide a good review of seed germination and vigor testing. Different classes of these tests are usually used including:

a. Standard germination test: This technique is used to test for the viability of seeds as affected by mechanical damage as well as other factors such as insect, disease, and others (Copeland and Mcdonald, 1995). Some mechanically damaged kernels might germinate as long as the embryo and a reasonable portion of the kernel remain undamaged. Chowdhury and Buchele (1976a) used a numerical damage index to correlate degree and severity of mechanical damage in corn with germination percent. They reported 0, 5, 38.6, and 76.5 percent germination for fines, severe damage, major damage, and minor damage respectively.

b. Acid germination test: This test was promoted by the National Institute of Agricultural Engineering, Silsoe, England. In this test, seeds are soaked for 3 hours at a 50 percent v/v of Sulfuric acid solution at 20-21 ^{0}C. Next, seeds are washed under running water and steeped for 15 minutes in excess of 2 percent calcium carbonate suspension, then washed with water again before being allowed to germinate. Sulfuric acid solution penetrates through the cracked seed coat and damages the embryo while it does not affect the sound seeds (Arnold, 1964). The main downsides of this method are the use of hazardous chemicals and that it is time consuming.

c. Seedling growth rate tests: This method is used to evaluate seed quality by placing seeds in a dark germination chamber at $25 \pm 1^{\circ}$C for seven days. The seedlings are dried at 80 $^{\circ}$C for 24 hours after germination, then the total dry weight of normal seedlings is divided by the number seedlings included to calculate the seedlings growth rate (Burris et al., 1969). Chowdhury and Kline (1976) used this method to evaluate the effect of internal damage from compression loading on the corn kernel.

d. Cold germination test: This method is commonly used by the hybrid corn and seed industry to evaluate the quality of seed and vigor of seedlings. This test is conducted on 200 seeds. In this test a cold stress of 10 $^{\circ}$C for 7 days is imposed on the seeds followed by a four day 25 $^{\circ}$C warm period (Copeland and McDonald, 1995). Tests of this method on cottonseeds showed an increase in germination percentage with decrease in mechanical damage (Welch and Delounche, 1969).

Breakage test methods:

Breakage tests were developed to help predicting damage susceptibility and evaluate the ability of grain to tolerate different handling operations. McGinty (1970) evaluated two commercial breakage testers, the Cargill grain breakage tester and the Stein breakage tester. He reported that the Stein breakage tester provided a better prediction of grain susceptibility to damage. The Stein breakage test predicts damage susceptibility by impacting 100 grams of grain for two minutes in the breakage tester cup and weighing the amount of the grain that is retained by a sieve 4.76 mm (12/64 round-hole sieve for corn). Stephen and Foster (1976) reported that the comparison between the actual handling and drying breakage data, and results obtained by the Stein breakage tester showed a good correlation.

Colorimetric method:

This method was developed by Chowdhury (1978). Mechanically damaged grain sample is soaked in a fast green FCF dye for one minute. The dye stains the starchy exposed part of the kernel. The dye is then drained and the excess dye is washed off from the grain sample by rinsing it under running water for 30 seconds. Next, a sodium hydroxide solution is used to extract the dye from the grain sample and the extracted solution is measured using a Beckman DB-G grating spectrophotometer. The concentration of the dye solution was found to be linearly proportional to the level of mechanical damage. He found that the technique is independent of corn variety and moisture content. The method is considered among the few practical mechanical damage measuring techniques.

Internal damage detection methods:

Internal damage and stress cracks are commonly found in mechanically shelled grains, those damage types are difficult to detect with the naked eye. Several methods were developed to assist in measuring those damages, which include:

a. Candling method: This method is used for detecting internal damage and stress cracks in corn kernels caused by drying and external loading. The system consists of a 150-watt incandescent light source enclosed in a box below a small rectangular glass covered window. The kernels are positioned on the window such that the embryo side is toward the light source (Thompson and Foster, 1963).

b. Topographical tetrazolium test: This method detects damage by cutting the seed longitudinally and staining the embryo with a one- percent solution of 2,3, 5-triphenyl tetrazolium chloride. Enzymes present in live embryo and uses the chemical as a substrate producing a red coloration (Lakon, 1949).

c. Chemical tests: This method is effective for legume seeds. The method was developed by Agriculture Marketing Service of the USDA. The seeds are immersed on an indicator solution of 100 milligrams iodoxyl acetate, 25-ml ethanol, and 75 ml distilled water. The seeds are then exposed to ammonium hydroxide fumes, and within a minute cracked seeds are stained blue (Waelti, 1967).

d. Infrared photographic technique: This method was reported to detect the difference between damaged and sound corn kernels, but failed to detect the difference between different levels of damage (Chung and Park, 1971).

Color sorting methods:

Color sorting techniques use the principle of color and/or brightness differences between grain kernels to sort them into categories using appropriate light sources and photocells. Boyd et al. (1968) used this technique along with germination tests to sort damaged seeds. They reported that seeds with cracked coat did not have enough color difference in the damaged area to allow damage detection, and the results were improved using dyed seeds as compared to unstained seeds.

Carbon dioxide production methods:

Steel (1967) studied the effect of corn mechanical damage, moisture content, and temperature on the rate of deterioration of wet, shelled corn. His study was based on the carbohydrate respiration equation, which is given as:

$C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O + 673$ Cal.

The increase in the rate of deterioration (or dry matter loss) caused by mechanical damage was calculated by measuring the correspondent increase in carbon dioxide production from the grain. The combustion of carbohydrates represented the grain respiration and the mold growth. In four hr duration test, it was found that moisture content was a much more important factor in determining the rate of carbon dioxide production than kernel mechanical damage. The procedure requires specialized equipment and considerable time. Kalbasi-Ashtari et al. (1979) reported a linear relationship between oxygen uptake and mechancial damage level for high moisture corn.

Water absorption methods:

Chung and Park (1971) examined the possibility of measuring grain mechanical damage on the basis of water absorption rates. They reported that the method can detect damage level based on water absorption rate, although it depends on initial moisture content, temperature, grain history, and the degree of damage. Therefore, they considered the method unpractical for grain grading based on damage.

Agness (1968) observed that damaged grain kernels absorbed water faster than sound kernels and the spectrophotometric analysis of the water extract from damaged grain samples showed more turbididty and greater soluble concentrations in the extracted water than sound kernel samples. However, it was difficult to distinguish among the different damage levels.

VanUtrecht et al., (2000) used sodium hypoclorite test to quantify soybeans mechanical damage. They reported that this method detects damage by causing the cracked soybean hulls to absorb the sodium hypochlorite solution and swell. They found that this method produced more consistent results compared to the idoxyl acetate test which is a dye-based technique, although, the idoxyl acetate test was more sensitive to mechanical damage levels.

Rheological methods:

Mahmoud and Kline (1972) observed a linear decrease of bulk density with increase in mechanical damage of shelled corn. They also found that compressive energy and relaxation time decreased linearly with increase in mechanical damage, while strain at a given load increased linearly with increase in damage. The gradient of those lines was not large enough to allow for detecting the differences among different levels of damage.

Electronic methods:

Holaday (1964) used the principle of moisture distribution within corn kernel to measure the heat-damage of artificially dried corn. His measurements were based on the corn capacitance and D.C. resistance. He found that the perpendicular distance from the capacitance-resistance line was an accurate index of drying damage in corn.

Photoelectric methods:

Christenbury and Buchele (1977) treated mechanically damaged corn kernels with a solution that contained 8-anilino-1-naphthalene sulfonic acid, that reacts selectively with internal protein that is exposed due to a crack or damage in the outer pericarp, in an attempt to measure mechanical damage in corn. The grain was then ground and ultraviolet light was used to relate the induced florescence with mass damage. They found a linear relationship between the measuring system and the mechanical damage of the sample.

Spectrophotometric methods:

These methods are based on the fact that optical properties of an object (transmittance, reflectance, and absorption) are affected by presence of defects. Norris (1958) reported that transmittance measurements have been found to be useful in detecting internal defects of agricultural products. The technique has been adopted by Neotc Instruments and others as a grain quality analyzer for determining moisture, oil, and protein in grain but no attempts have been made to evaluate mechanical damage in grain. Gunasekaran et al. (1984) developed an optical method using a low power helium-neon laser source to detect the defective corn kernels. The method was based on the reflectance difference between sound and defective corn kernels. They reported that the method was able to detect the broken, chipped-off, and starch-cracked kernels with nearly 100 percent accuracy, and minor splits and cracks with about 80 percent accuracy.

Grinding energy method:

Ali (1981) reported that grinding energy for corn samples decreased linearly with increase in damage level and moisture content. He observed that the best linear relationship between grinding energy and mechanical damage level was at corn moisture contents between 20 and 23 percent. He found also that grinding rate increases with increase in damage level and moisture content and he concluded that grinding rate was a better indicator of mechanical damage level than grinding energy.

Acoustic method:

Misra et al. (1990) used this technique to detect soybean damage caused by diseases. The method uses the characteristics of the impulse wave that results from dropping each soybean into an acoustic transducer to characterize the several seed properties using a computer program. The method has not been shown to distinguish the different levels of mechanical damage. Ultrasonic imaging was used by Gunasekaran and Paulsen (1984) to detect corn kernel defects. They reported that the method was not effective since the intercellular spaces in the corn kernel impeded sound wave transmission through the whole kernel.

Electrical conductivity method:

This method predicts kernel damage by measuring the electrical conductivity of the solution that contains the solid particles that leach from a fixed number of seeds after soaking them for 18 to 72 hr, depending on the type of the seeds (Hopper et al., 1980). Couto, et al. (1998) used a modified method for detecting soybeans mechanical damage. This method increased the relative number of grains per volume of water and introduced stirring process to shorten the test time. The solution conductivity was recorded at 20 minutes intervals for 160 minutes. A linear relationship was observed between mechanical damage and electrical conductivity for one soybeans variety and a quadratic relationship for the other variety used in the test. These relationships existed at each soaking time except for the initial time. They concluded that the method allowed for the measurement of mechanical damage in soybeans after 20 minutes.

Machine vision methods:

Machine vision systems operate on the principle of color differences among samples. In a typical classification system, a training set is used to extract the color and other related features of calibration samples to classify unknown samples unknown samples based on the calibration information.

Gunasekaran et al. (1988) used a commercial computer vision system to evaluate corn and soybeans physical damage as well as other quality factors. They used the system to detect corn mechanical damage generated by placing grain samples in a centrifugal impactor. Four varieties of corn with 25 kernels from each variety were used. The system was able to detect corn physical damage with 100, 83, 88 percent success, for broken, chipped, starched-cracked samples, respectively.

Ng et al. (1998) used color image analysis to identify the mold damage in corn kernels. They reported that the identification results of mold damage obtained from this system and from a neural network classifier were in agreement with the measurement made by the laboratory workers.

Luo et al. (1999) used color machine vision system to identify six levels of damage in red spring wheat. They reported that a combination of color and morphological features was able to identify kernel damage with accuracy ranging from 90 to 100 percent. They concluded that the system could be practically used for grain identification.

Machine vision systems have the advantage of providing a nondestructive analysis of grain damage, however, they have the limitation of sensitivity to optical noise and inability to detect internal defects of the grain.

The methods discussed so far had their specific applications. Although some of those methods were more successful in evaluating mechanical damage, they had several shortcomings. A more practical method would involve developing a fast and automatic technique for measuring mechanical damage.

CHAPTER 3: MEASUREMENT OF CORN ARTIFICIAL AND COMBINE MECHANCIAL DAMAGE USING DIELECTRIC PROPERTIES

Introduction

The introduction of mechanical grain shelling has resulted in a greater magnitude of mechanical damage during harvest, which in turn increased the rate of damage and deterioration during subsequent transportation, handling, and storage. There has been no agreement among researchers on a standard definition or measurement methodology of grain mechanical damage. Grain mechanical damage causes some quality loss. This includes faster deterioration, lower profit, easier fungal invasion, greater insect manifestation, higher breakage susceptibility, and lower processing quality among others (Saul and Steel, 1966; Freeman, 1970; Paulsen and Nave, 1981; Ng et al., 1998; Almeida-Dominguez et al., 1998).

Reports on grain mechanical damage level, varied in literature. Earlier studies showed that mechanical damage varied between 16.5 and 40 percent, depending on the method used to evaluate damage (Mahmoud and Buckele, 1975; Chowdhury and Buchele, 1976a; Kalbasi-Ashtari et al., 1979). More recent studies, however, showed that damage ranged from 5 to 10 percent (Paulsen and Nave 1980; Quick 2001, Melvin 2001). The ASAE defined mechanical damage as visual and hidden damage caused by mechanical harvesting (ASAE 1999). Mechanical damage was defined by Brass (1970) to include all categories of physically chopped or cracked corn kernels. Chowdhury and Buchele (1975) defined damage by categorizing it into four major groups: minor, major, severe damage, and fines. USDA

Official grain grading system correlates damage with the portion of the grain that passes through a round hole sieve (USDA 1999).

Studies found that this grading system accounts for a small fraction of the total mechanical damage (Chowdhury and Buckele, 1976a; Kalbasi-Ashtari et al., 1979). Therefore, extensive research has been done in an attempt to develop more efficient methods for evaluating mechanical damage. Some of the most commonly used in research include, visual inspection, where the grain kernels with any visual damage or cracks are picked up from the grain sample then weighed (Koehler, 1957; Schmidit et al., 1966; Mahmoud and Kline, 1972; Chowdhury and Buchele, 1975). Germination tests were also used to evaluate mechanical damage by correlating damage with the ability of the grain kernel to emerge and develop a reasonably healthy seedling (Chowdhury and Buchele, 1976b). This method, however, is affected by other types of kernel damage as well. Colorimetric methods, which correlate the damage level of a grain sample with the absorbency or transmittance of light through a dye extraction solution obtained from that sample was also used (Chowdhury, 1978). Machine vision has recently found some use. The grain kernels are classified based on certain color or texture features (Gunasekaran et al., 1988; Ng et al., 1998; and Luo et al., 1999). Electric conductivity methods were also successfully used to correlate mechanical damage to the amount of solid leachates from cracked soybeans samples (Hopper et al., 1980; Couto et al., 1998).

Dielectric measurements of grains based on the complex electric capacitance and impedance have been successfully used to develop sensors for measuring moisture content and bulk density of grains (Nelson et al., 1977; Berbert et al., 1996; Kraszewski et al., 1998; Lawrence et al., 1998; Trabelsi et al., 1999). The effect of dielectric properties on other grain quality factors was also investigated. Grain kernel size was found to affect the dielectric constant of grains at the microwave frequencies at which the kernel dimensions were not large enough compared to the wave length (Jones et al., 1978; Nelson, 1979a). The electrode spacing was also reported to affect the dielectric properties of grains (Jones et al., 1978; Nelson, 1979a). They found that smaller electrode spacing resulted in smaller dielectric constant. Holaday (1964) investigated the effect of several chemical and physical parameters on the damage associated with high temperature drying of corn. He reported that the moisture distribution associated with corn drying was a fast and accurate measure of this type of corn damage. He used the DC resistance and the AC capacitance of the corn samples dried at 82 ^{0}C (180 ^{0}F) to develop this relationship. He observed that the normal distance measured from the line plotted between the logarithm of AC resistance and DC capacitance of the dried corn samples was an accurate measure of the degree of corn damage associated with high temperature drying. The method he used was essentially based on the correlation between the dc resistance and the dielectric constant of the dried corn samples and the drying damage associated with the sample

Venkastesh et al. (1998) found that size reduction of the grain samples had some effect on their dielectric response. They investigated the response of dielectric variables to whole, chopped, and powdered corn samples using cavity perturbation technique to measure dielectric properties at 915 MHz and 24 ^{0}C. They found a linear relationship between bulk density of the corn sample and the cubic root of the dielectric constant and a similar relationship between the bulk density and the square root of the dielectric loss factor. Corn samples chopped to different degrees were found to have different dielectric properties at similar bulk densities and moisture contents indicating that some of the response was due to particle size effect or chopping. They also reported that the results were not conclusive, since slight differences in moisture content and composition as well as measurement errors might have existed and could have had some affect on their results. They explained their observations by the fact that cross-sectional moisture and material gradients in a single grain kernel might have an effect on the dielectric response of that kernel since these gradients affect the power density attenuation.

Therefore, an experiment that investigates the effect of mechanical damage as well as other factors on the dielectric response was designed. The experiment was designed carefully to account for the effect of moisture content, bulk density, and other factors that were proven to affect dielectric response of grain samples. This study was based on the assumption that mechanical damage has a measurable effect on the dielectric properties of corn kernels. In addition it assumes that it has an effect on the material and moisture gradients of the corn kernel, which affect the power density attenuation of the applied electric field in the corn kernels and therefore the dielectric response of these corn sample (Holaday, 1964; Venkastesh et al.;1998).

Objectives

The objectives of this research project are:

1. To define the effect of artificial mechanical damage on the dielectric properties of corn using two types of artificial damage.
2. To define the effect of combine damage caused by mechanical harvesting on dielectric properties of corn.

3. To define the possibility of developing a mechanical damage sensor that could be used to measure mechanical damage level quickly and accurately. This will be tested using artificially prepared mechanical damage and combine mechanical damage from mechanical harvesting.
4. To define the proportional effect and contribution of moisture content and bulk density to the overall dielectric response of corn samples, and the possibility of developing moisture and bulk density sensors using the dielectric properties.

Material and Methods

The experiment consisted of two parts. In the first part, artificial damage was prepared in the laboratory and its effect on dielectric response was investigated. In the second part, combine damage was produced under field conditions and its effect on dielectric response was studied as well. The corn used for artificial damaged experiment was a clean corn (*Zea Maize*) of unspecified variety, which was brought from GARST Seed Company*, Slater, Iowa. Moisture content of corn was determined using ASAE standard method by weighing triplicate 15 g corn samples in aluminum weighing dishes and drying the samples for 72 hr at 103 ^{o}C in a forced air oven (ASAE 1991). Moisture content was found to be 11 % (W. B.). All moisture contents were calculated on wet basis. The corn used for combine damage experiment, was a clean corn (*Zea Maize*), variety ( ), which was harvested in the Agricultural Engineering Research Farm, Ames, IA, during summer 2000. A JD 4420 combine was used and moisture content was found to be 12.5 % (W.B.).

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* The trade names are provided for the benefit of the reader only.

Mechanical damage preparation

One of the objectives of this study was to investigate the effect of mechanical damage on dielectric properties of corn. For the artificial damage experiment, two types of artificial damage were prepared in the laboratory in an attempt to simulate corn mechanical damage that usually results from mechanical harvesting, handling, and transportation of corn. Medium and severe mechanical damage were prepared using two different pieces of laboratory equipment. Severe damaged samples were prepared using a roller mill (Dry Corn Milling Inc, Wichita, KS). The roller mill had three levels of corrugations: fine, medium and rough corrugation. The rough corrugation was found to achieve the best uniformity in size reduction and the least fines fraction and was used to produce the severe damaged corn samples. The clearance between the two counter-rotating rollers was adjusted to 0.3 cm. Thirty-five kg of clean corn at 11 % MC were damaged using this method. The resulting samples were sieved using a 4.76 mm (12/64 in) round-hole sieve. All fines and other fractions that passed through the sieve were discarded, because those part are usually blown away by the combine fan. The samples were then bagged in airtight plastic bags and stored at 4°C to preserve quality until later use. The medium damaged corn samples were prepared using the Stein Breakage tester by placing 200 g of sound corn kernels at 11% MC in the Stein Breakage tester cup and turning on the impeller for 15 minutes. The sample was then sieved using a 4.76 mm (12/64 in) round-hole sieve. Finally, any undamaged kernels were hand picked and removed from the sample. This procedure was repeated to produce a total of 35 kg of medium damaged corn. Although this procedure was time consuming, the results showed excellent repeatability. Images of the severe damaged, medium damaged, and undamaged kernels are shown in figure 3.1. For combine damaged corn samples, three levels of mechanical damage were obtained by running the combine at three different operating conditions in the field. The first combine run was made at a cylinder rotational speed of 420 rpm, the second run was made at 620 rpm, and the last run was made at 820 rpm with a concave-cylinder clearance closer than the first two runs by 3.75 mm (1/8 inch) and with the combine blower turned off. The objective of these adjustments was to obtain three different levels of combine mechanical damage. Undamaged corn samples were also obtained by hand shelling corncobs to obtain undamaged corn samples. Moisture content was determined for all three combine damaged levels and undamaged corn samples and was 12 %. The combine harvested corn with the damaged kernels were dyed in green color using the Fast Green FCF Dye to facilitate visual inspection as shown in figure 3.2.

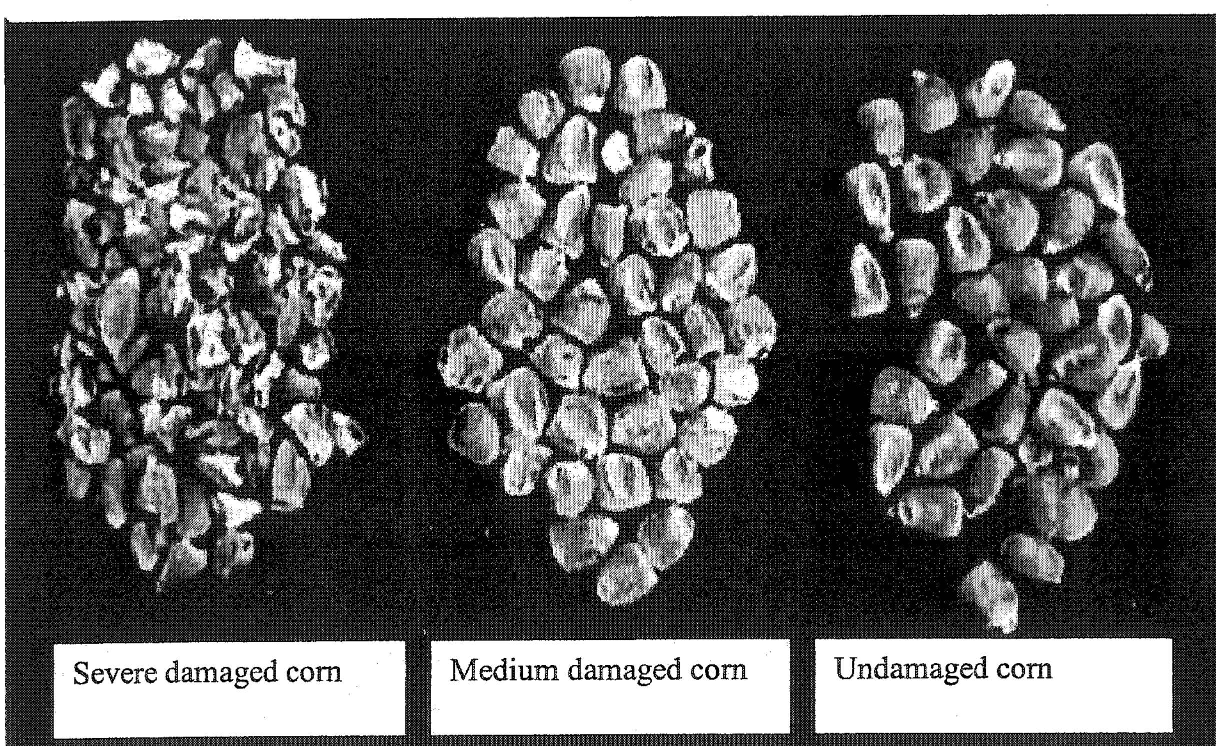

Figure 3.1. Photograph of different artificially damaged corn samples.

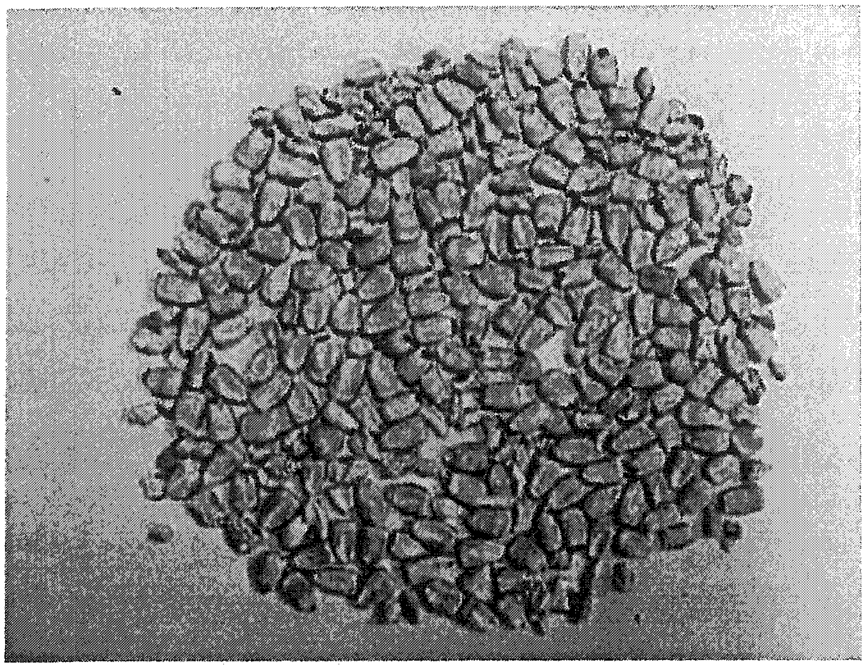

Figure 3.2. Photograph of combine harvested corn with damaged kernels dyed in green color

Moisture content adjustment

For artificially damaged corn samples; two levels of moisture content were prepared in order to investigate the effect of moisture level on the dielectric response of the corn samples. The corn samples were adjusted into 11 percent, and 19 percent moisture content (WB)[1]. The two moisture levels were chosen to represent the low and medium moisture range. To obtain the low moisture content, all corn samples were slightly adjusted by adding a small amount of distilled water to bring them to the same moisture level of 11 percent. The high moisture samples were prepared by adding additional amount of distilled water into half of the corn samples at 11% moisture content to bring them to 19 % moisture content. Water was added to each 1 kg corn bag separately at two steps. In the first step water was added to

[1] All moisture contents reported are wet based.

bring the corn moisture from 11 to 15 %, then the samples were sealed in the 1 kg bags and stored at 4°C for 10 days with frequent thorough mixing in order to make sure that moisture was uniformly distributed throughout the whole 1 kg sample. In the second step, more distilled water was added to bring the corn moisture content to 19 %. The samples were then stored again at the same conditions for another 14 days with daily mixing. Each corn mechanical damage type (medium, severe, and undamaged) was adjusted for moisture content separately. At the end of the 14 days period, random samples of corn were drawn from bags of low and high moisture and moisture contents were measured using the standard ASAE method (ASAE standard, 1991) to ensure that moisture was correctly and uniformly adjusted. For Combine damage, three levels of moisture content representing the low, medium, and high moisture were prepared (12.5, 18, and 23%). The moisture content was adjusted by adding a specific amount of distilled water to the corn samples similar to the artificially damaged samples.

Damage level preparation and measurement

The artificial damage samples consisted of five different damage levels (percentages). The different damage levels were prepared by mixing the appropriate mass proportions of damaged and undamaged corn. The five levels of damage produced were 0, 10, 25, 50, and 100 %. Experimental units of 1 kg corn sample were produced. Each experimental unit represented a combination of one moisture content and one damage level. The units were prepared for medium and severe damage samples separately. Therefore, 19 different samples representing the combinations of five damage levels (0, 10, 25, 50, and 100 percent), two damage types (severe and medium) and two moisture contents (11 and 19 percent) were obtained, with five replicates of each treatment. The resulting experimental design, therefore,

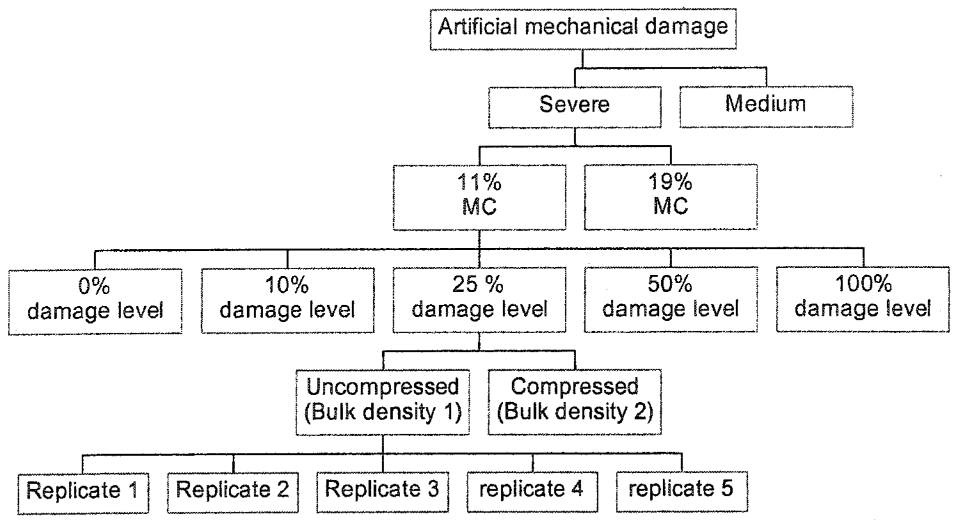

Figure 3.3. Experimental design for testing of artificially damaged corn.

represented a nested structure as shown in figure 3.3. All samples were double bagged, sealed, and stored at 4°C for dielectric measurements.

For combine damage, three mechanical damage levels were obtained by varying the combine operating conditions, while the fourth level (undamaged corn) was prepared by hand shelling corn. All samples were sieved and cleaned using a laboratory air screen cleaner (Kams Westrup). The system uses mechanical shaking and air flow to clean grain, was set up to remove light weight fines, foreign materials, and particles with sizes larger than 9.53 mm (24/64 in) or smaller than 4.76 mm (12/ 64 in) opening of a round-hole sieve. The experimental design for combine mechanical damage is shown in figure 3.4. Corn mechanical damage for those samples was then measured using the Chowdhury method (Chowdhury, 1978) and quantitative visual inspection (Chowdhury et al., 1976). In Chowdhury's method, mechanical damage percentage (level) was evaluated by randomly

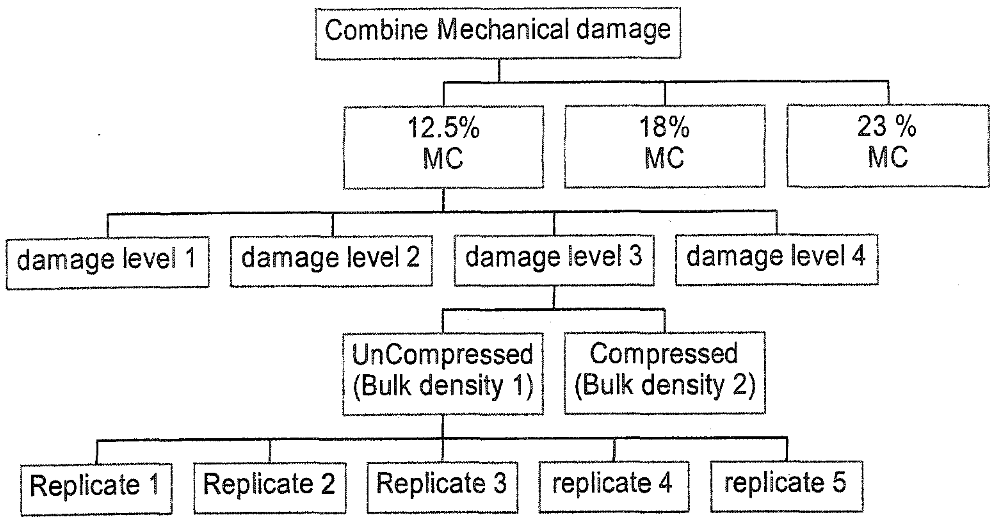

Figure 3.4. Experimental design for testing of combine damaged corn.

picking up a 400 g of corn from each damage level. Then a 100 g sample was obtained using a Boerner grain divider. The sample was then soaked in a fast green FCF dye for one minute, which stains the starchy exposed part of the cracked kernels. The dye was then drained and the excess dye was washed off from the grain sample by rinsing it under running water for 30 seconds. Next, a sodium hydroxide extraction solution was used to extract the dye from the grain sample and the extracted solution was read using Chowdhury's grain quality meter. The meter correlates the concentration of the dye in the extraction solution to the degree of mechanical damage and provides a direct reading of mechanical damage percentage. The test was repeated three times for each damage level. In the quantitative visual inspection test, three-400 g samples of corn were randomly drawn from the corn lot. Then 100 g were obtained from each sample using a Boerner grain divider. Next, the sample was sieved using a 4.76 mm (12/46 in) round-hole sieve and the portion that passed through the sieve was weighed. The remaining corn kernels were soaked in a 0.1 percent Fast Green FCF dye for 4 minutes to facilitate visual inspection and the excess dye was washed away using running water. Dyed kernels were then spread out on a paper towel and left to dry for 24 hr and the kernels were inspected one by one for any visual mechanical damage. The kernel was considered damaged if it was broken, chipped, cracked, bruised or had hairline cracks.

Quantitative visual damage evaluation techniques do not discriminate among the different types of mechanical damage (severe damage, medium damage, cracks, etc.) and therefore, any cracked or chopped kernel was counted for the purpose of measuring damage. Chowdhury's method, on the other hand, accounted for the degree of damage in the corn kernel, since it correlates damage percentage to the proportion of the starchy exposed area of the corn kernel, which depends on the severity of damage in the kernel. Chowdhury's method, however, does not account for any damage that does not result in exposing starchy part of the kernel, because the dye has the ability to stain the starchy part of the cracked kernels only. Since both damage types had advantages and shortcomings, both of them were used as the reference damage for predicting damage percentage using dielectric properties. The different types of mechanical damage that resulted from combine harvest defined according to their degree of damage are shown in figure 3.5 through 3.9.

Figure 3.5. Hand shelled undamaged corn kernels.

Figure 3.6. Combine harvested corn with minor kernel damage.

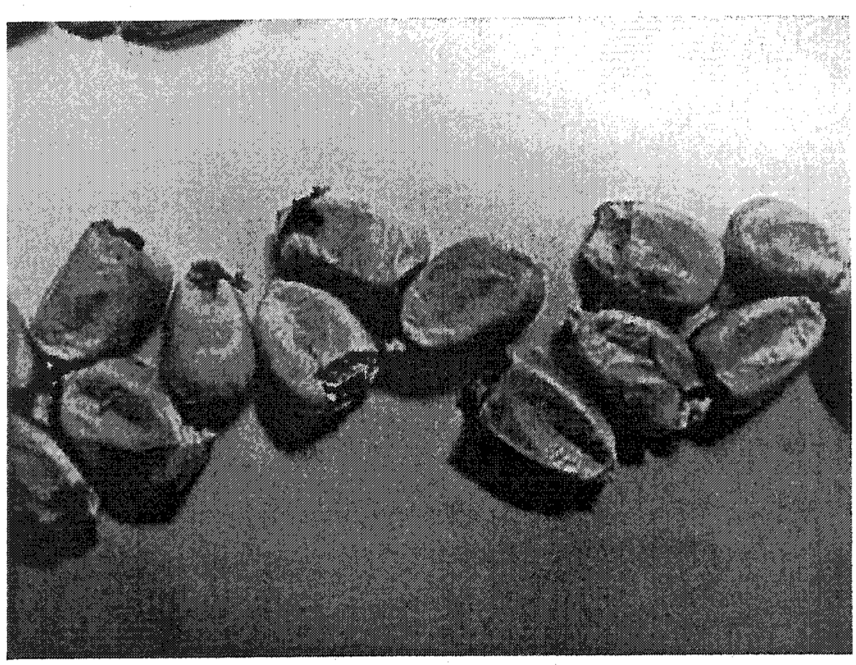

Figure 3.7. Combine harvested corn with medium kernel damage.

Figure 3.8. Combine harvested corn with major kernel damage.

Figure 3.9. Combine harvested corn with severe kernel damage and splits.

Electrical measurements

The procedure for obtaining dielectric measurements for artificially damaged and combine damaged corn samples was essentially the same. Dielectric measurements were obtained using a Hewlett-Packard 4192A LF impedance analyzer controlled by a personal computer with a Pentium I processor. A GPIB, CBI-488.2 General Purpose Interface Board (ComputerBoard, Inc. Middleboro, MA)[2] was installed into the computer to be used for controlling the impedance analyzer. A control program was written using QuickBASIC to allow automatic measurement of dielectric parameters. The interface board enabled the computer to communicate with the impedance analyzer, specify the impedance settings, set the parameters to be measured, and start the measurement series using the QuickBASIC program code. The impedance analyzer was connected to the sample holder via an HP 16095 Probe fixture. The sample holder was a vertically-oriented parallel-plate electrode assembly, similar to the one described by Lawrence, et al. (1993). It consisted of three square-shaped aluminum plates (15 x15 x 0.48) cm, separated apart by 2.54 cm using Rexolite 1422 insulating plates. The sample holder had two equal compartments, which represented two parallel-plate capacitors with the middle electrode representing the active terminal and the outer electrodes as the ground (figure 3.10). The total volume of the sample holder was 1143 cm^3. In order to make a secure electric connection, a coaxial BNC mounting was connected to a small rectangular aluminum plate. A 4-40 brass machine screw was soldered to the BNC center connector and then screwed to the middle electrode. The outer electrodes were

[2] Mention of the commercial names is provided for the benefit of the readers and does not imply endorsement by Iowa State University.

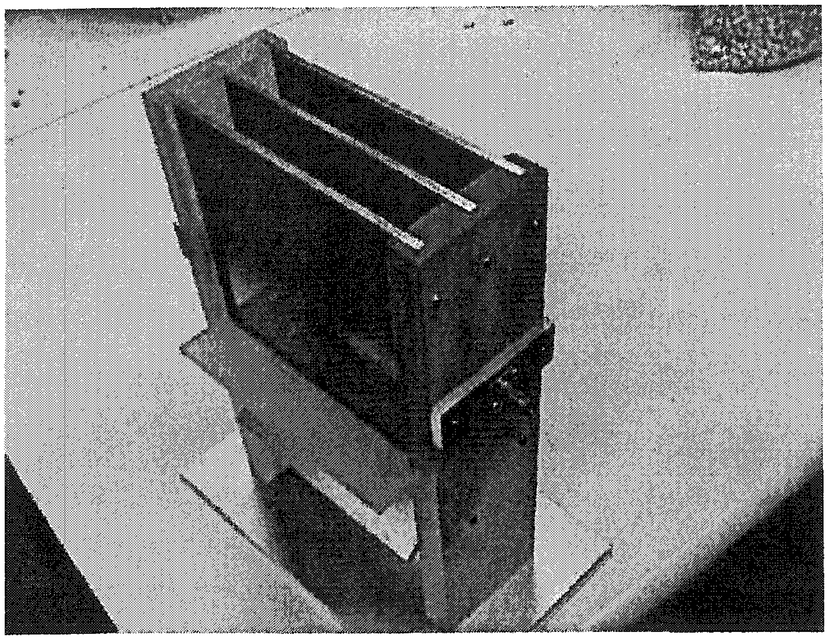

Figure 3.10. The sample holder used for measuring dielectric properties of corn samples.

connected to the ground by two 4-40 brass machine screws that were screwed to the small aluminum plate then to the BNC connector (Lawrence et al. 1993). Another small aluminum piece was connected to the opposite side of the aluminum plate in the BNC connector side, and a 4-40 brass machine screw was used to make the short-circuit connections in the series circuit mode. The complete measurement system is shown in figure 3.11. To obtain the dielectric measurements, the relative complex permittivity (ε_r), which consists of dielectric constant (ε'_s) and dielectric loss factor (ε''_s) was measured. The complex admittance of the material, $Y = G + jB$, where G represents the conductance and B represents the susceptance were obtained. The two quantities were obtained directly from the impedance analyzer using the parallel circuit mode. Lawrence et al. (1993) derived an expression for the dielectric constant and loss factor for a similar sample holder. They used the empty sample holder

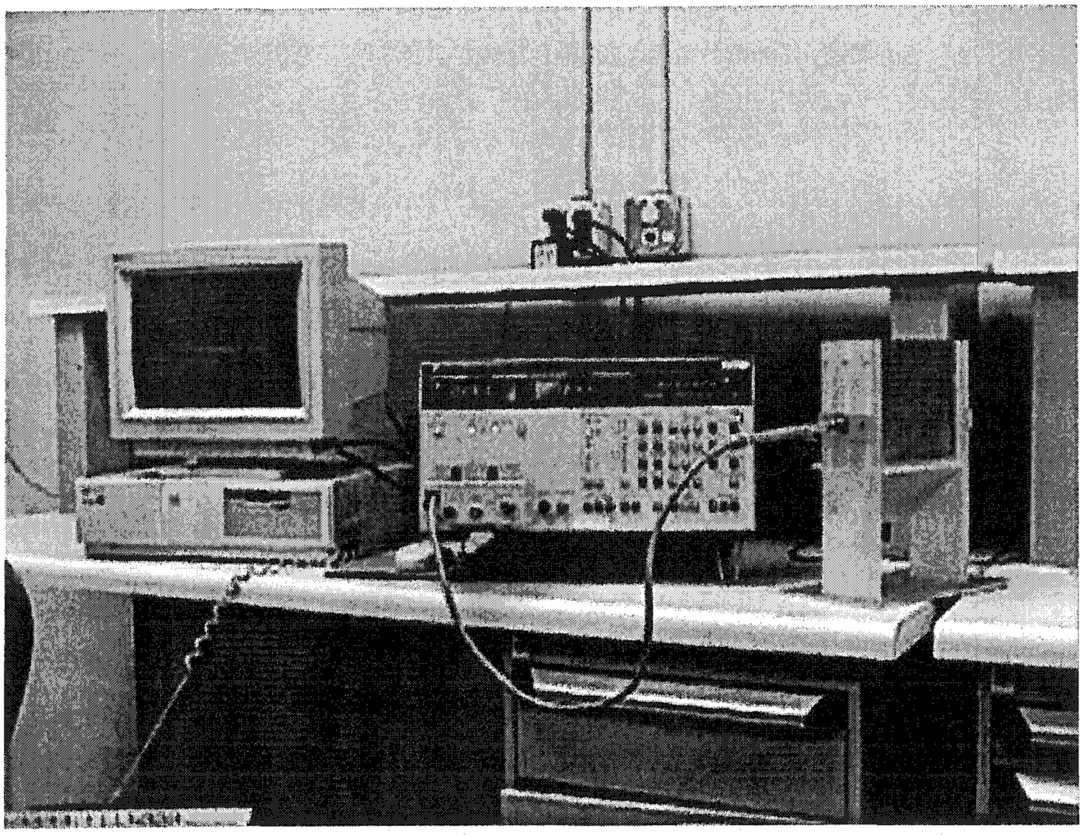

Figure 3.11. Photograph of complete measurement system with sample holder (right), impedance analyzer (middle), and computer control (left).

measurements to eliminate the effects of fringing field, connecting cable, and stray capacitance (Lawrence et al. 1993). The sample holder was modeled by a two parallel-plate capacitors connected in parallel as shown in figure 3.12. This model was used to derive an expression for the dielectric constant and loss factor as follows:

1. Dielectric constant (ε'):

a. Empty sample holder measurement:

$$C_a = 2\,C_0 + 2\,C_R + C_f \tag{3.1}$$

Where: C_a : measured air-filled capacitance in pf.

C_0 : Capacitance of the sample region of the capacitor with air as a dielectric material in pf.
C_R : Capacitance associated with Rexolite in pf.
C_f : Capacitance associated with fringing field in pf.

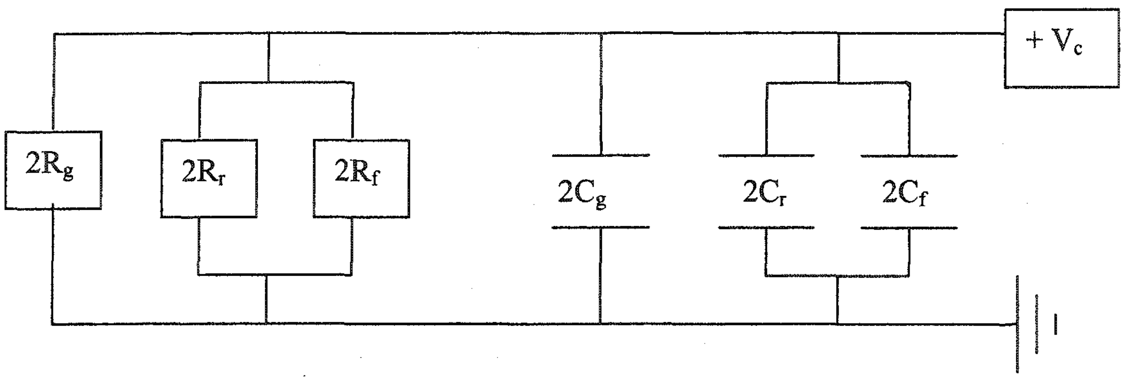

Figure 3.12. Equivalent circuit for dielectric measurements where R_g, R_r, & R_f, and C_g, C_r, and C_f are the resistance and the capacitance associated with grain, Rexolite, and fringing field.

b. Grain-filled sample holder:

$$C_m = 2\ C_s + 2\ C_R + C_f \tag{3.2}$$

Where: C_m : measured total capacitance of the sample holder filled with grain in pf.
C_s : Capacitance of the grain sample in pf.
C_R : Capacitance associated with Rexolite in pf.
C_f : Capacitance associated with fringing field in pf.

By subtracting equation (3.1) from (3.2):

$$C_m - C_a = 2\ (C_s - C_0) \tag{3.3}$$

However, $C_s = \varepsilon'_s\ C_0$, substituting to (3.3) and rearranging

$$\varepsilon'_s = \frac{C_m - C_a}{2C_0} + 1 \tag{3.4}$$

C_0 can be calculated from the given geometrical parameters of the capacitor

$$C_0 = \varepsilon'_a \, \varepsilon'_0 \, \frac{A_0}{d} \tag{3.5}$$

Where: ε'_a = dielectric constant of air ($\cong$ 1).
ε'_0 = permittivity of space (8.84194×10^{-12}).
A_0 = capacitor area
D = distance between the capacitor plates

By substituting these parameters into equation (3.4):

$$\varepsilon'_s = \left(\frac{C_m - C_a}{2} - 3.36 * 10^{-12} \right) 0.1275 * 10^{12} \tag{3.6}$$

Since B = C * ω = C*2πf, the above expression could be expressed in terms of B as follows:

$$\varepsilon'_s = \left(\frac{B_m - B_a}{4.\pi.f} - 3.36 * 10^{-12} \right) 0.1275 * 10^{12} \tag{3.7}$$

2. Dielectric loss factor (ε''):

a. Air-filled sample holder:

$$G_a = 2G_0 + 2G_R + G_f \tag{3.8}$$

Where: G_a : measured total conductance of empty sample holder in mS.
G_0 : Conductance of the sample region with air as a dielectric material ($G_0 \cong 0$).
G_R : conductance of the sample region of capacitor with Rexolite as a dielectric material in mS.
G_f : error conductance in mS.

b. Grain-filled sample holder:

$$G_m = 2G_s + 2G_R + G_f \tag{3.9}$$

Where: G_m : measured total conductance of the grain sample in mS.
G_s : Conductance of the grain-filled portion of the sample holder.
G_R : conductance of the sample region of capacitor with Rexolite as a dielectric material. In mS.
G_f : error conductance in mS.

Subtract (3.8) from (3.9),

$$G_m - G_a = 2\,(G_s - G_0) \tag{3.10}$$

And $G_s = \omega\, C_0\, \varepsilon''_s$, substituting G_s to (3.10) and solving for ε''_s :

$$\varepsilon''_s = \frac{G_m - G_s}{2\omega . C_0} + \frac{G_0}{\omega . C_0} \tag{3.11}$$

Since G_0 is negligibly small:

$$\varepsilon''_s = \frac{G_m - G_s}{2.\omega . C_0} \tag{3.12}$$

However, $C_0 = 6.5064*10^{-12}$ F and $\omega = 2\,\pi\, f$, where f is the frequency in Hz, therefor:

$$\varepsilon''_s = 1.2231*10^{10}\left(\frac{G_m - G_s}{f}\right) \tag{3.13}$$

The system was calibrated using butanol, a polar alcohol with known dielectric properties that could be predicted using Debye equation (Debye, 1929). The measurement system was then verified using published dielectric properties of corn samples with known moisture content after adjusting for bulk density. The results were in agreement with published data on dielectric properties (Stetson and Nelson 1972). Measurements of conductance (G) and suseptance (B) were obtained for air filled (empty) and grain filled sample holder (a total of four measurements), which were used to calculate the dielectric parameters (ε'_s and ε''_s) at each measurement frequency according to the model developed previously by Lawrence et al. (1993). This configuration allowed for eliminating the effect of fringing field and stray capacitance, and was found useful in predicting dielectric properties of corn at the frequency range from 5 Hz to 13 MHz.

Measurements procedure

Before starting measurements, corn samples were removed from cold storage and placed on a table to reach the room temperature of 25 ^{0}C. The impedance analyzer was turned on at least an hour before taking any measurements to allow for warm up as specified by the operator manual. The first series of measurements was taken with an empty sample holder (air filled). In order to cover the whole frequency range of the impedance analyzer, six cycles of measurements were programmed to the control program in the following order: First cycle: 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100 Hz, second cycle: 200, 300, 400, 500, 600, 700, 800, 900 1000 Hz, third cycle: 2, 3, 4, 5, 6, 7, 8, 9, and 10 kHz, fourth cycle: 20, 30, 40, 50, 60, 70, 80, 90, and 100 kHz, fifth cycle: 200, 300, 400, 500, 600, 700, 800, 900, and 1000 kHz, and sixth cycle 2, 3, 4, 5, 6, 7, 8, 9,10, 11, 12, and 13 MHz. Therefore a total of 58 frequencies were used, and two parameters were obtained at each frequency. Susceptance (B), which was used to estimate dielectric constant (ε'), and conductance (G), which was used to estimate the dielectric loss factor (ε"). The impedance analyzer was programmed to sweep through the whole measurement range twice. Corn samples were picked randomly and poured to the sample holder using a Fairbanks test weight apparatus as shown in figure 3.13. Excess corn was removed using a strike-off stick and a measuring sequence was initiated. The corn retained by the sample holder after removing the excess grain was accurately weighed before and after measurements to check for any changes in moisture content. Bulk density was calculated by dividing the corn weight by the total volume of the sample holder. Grain temperature and relative humidity were obtained using a digital humidity/temperature meter (Fisher Scientific), and were entered to the data file at the beginning of each measurement series. All measurements were obtained between 21-24 ^{0}C and 33-37 % RH. The total time needed to load, take measurements, and unload each sample was about five minutes. After finishing each measurement, an additional 3 percent of the original corn weight in the sample holder was added and compressed to produce another bulk

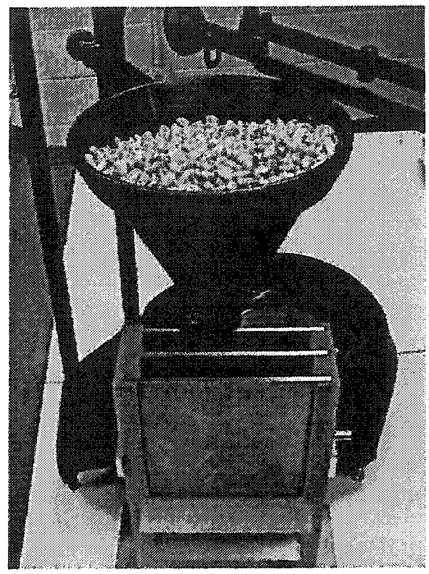

Figure 3.13. Fair Banks test weight apparatus.

density. All raw measurements were saved to the hard drive then transferred into a floppy disk for later post-processing and analysis. The procedure was then repeated by randomly picking up one of the 18 samples that represented the different combinations of damage type, moisture content, and damage level. After finishing the first replicate, similar procedure was repeated for the other four replicates and for the combine damaged samples. In order to keep a record of the moisture content of each sample measured, a corn sample was drawn for moisture measurement at the beginning of each run.

Statistical methods

Evaluation of relative dielectric response of moisture content, bulk density, and mechanical damage

Since the dielectric response of the measured samples represents the net effect of the three variables studied in the experiment (mechanical damage, moisture content, and bulk density), the proportional effect of each variable on the measured dielectric response was investigated using Analysis of Variance (ANOVA). Therefore, SAS Proc Mixed (SAS 1999) was used to check for the significance and proportional weight of each variable involved in the experimental design. The dielectric measurements (dielectric constant and loss factor) were assigned to the response variable one at a time and the procedure was run for every fifth frequency starting at 10 Hz. Proc mixed was used because the experiment was a nested design (figure 3.3) with both fixed effects (moisture content and damage level) and random effects (bulk density). This analysis was done for medium and severe damaged samples separately, then for combine damaged corn samples.

Variable selection and multivariate analysis

The next step after investigating the significance of the different variables on the dielectric properties was to screen for the dielectric variables which had the best predictive capacity and to use those screened variables to develop a calibration model that predicts mechanical damage level (assuming that mechanical damage turned out to be significant in the first step). The purpose of the variable screening method was to help reducing the number of dielectric variables (predictor variables) measured in the experiment without reducing the predictive capability of the model. Two methods were investigated to accomplish that. In the first method, the principle component analysis loadings using SAS PCA (SAS 1999) were inspected in an attempt to pick up variables with the highest loadings. This method gives the loading of each dielectric variable based on it's contribution in explaining the variation in the predictor variables. The dielectric variables loading were inspected for any influential variables. PCA and has the ability to handle multicollinearity by reducing the original variables into a few orthogonal principal components that explain the majority of variation in the original variables. A principal component is the linear combination of the original variables. Since the principle components are orthogonal, they are in essence independent

(Williams et al. 1990). However, it should be pointed out that this method reduces the original variables into few components or latent factors but does not reduce the number of the original predictor variables, since the new components or latent factors are a linear combination of all the original predictor variables. In the second method, Multiple Linear Regression SAS MLR, (SAS 1999) was used to screen the dielectric variables that best describe the variation in the response variable (mechanical damage level). Multiple linear regression uses optimization algorithms to select the predictor variables that explain most of the variability in the associated response variable. MAXR option of this technique can be used to pick up the n-number of variables that best describe the response by searching for the variables that maximizes the multiple coefficient of determination (R^2). Therefore, this algorithm selects the best one variable, two variables, three variables, and so forth, then it performs a statistical significance test every time a variable is added to the model. A check is performed on the new variable as well as the old variables that are already included in the model to assure that they are still statistically significant, which in turns minimizes the problem associated with multicolinearity. This technique, however, is not completely insensitive to multicolinearity problems and can not be guaranteed to choose the best variables. This method, however, provides a very reasonable tool for initial screening of the predictor variables. The only actual risk is associated with using multiple linear regression in the case of multicolinear variables (such as the predictor variables in this experiment) is when attempting to establish a cause and effect relationship, or to make inferences about the individual regression coefficients (William, et al. 1989). This is not a concern in this study, however, since calibration and prediction rather than inference are the objective of regression. After screening the predictor variables, SAS Proc GLM (SAS 1999) was used for developing the calibration model. After developing a calibration model using the existing damage data, the model should be tested to predict mechanical damage levels for new observations. This can be done by two methods. In the first one, a new set of external samples could be used to verify the ability of the calibration model to predict the new samples. This method, however, is limited by the availability of new samples, and therefore, the second method, which is based on using cross-validation was used. In cross validation, the samples are split into calibration (training) and verification parts, then the samples used for verification are excluded from the calibration model and then predicted using that calibration model. Therefore, the ability of the model to predict new observations was tested using Partial Least Square regression SAS Proc PLS (SAS 1999), which established cross validation to verify the robustness of the developed model to predict new observation without a need for additional samples.

Results and Discussion

Artificial mechanical damage

The relationship between bulk density of corn samples and percent mechanical damage is shown in figure 3.14 for severe and medium artificial damage at two levels of moisture content (11 and 19 %). For severe damaged samples, a strong correlation existed between bulk density and damage percent with R^2 = 0.98 and 0.93 for 11 and 19 % moisture content respectively. A much lower correlation between bulk density and mechanical damage level existed for medium damaged samples with R^2 = 0.19 and 0.01 for 11 and 19 percent moisture content, respectively. This relationship was expected since severe damaged samples

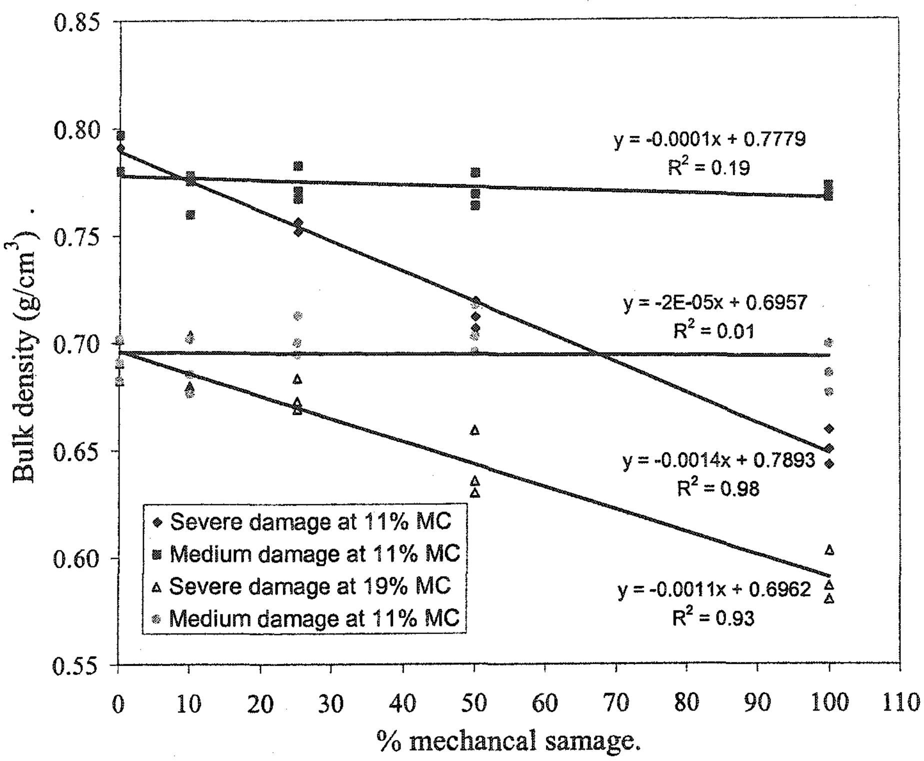

Figure 3.14. Relationship between bulk density and damage level for severe and medium damaged corn samples at 11 and 19 percent moisture content.

undergone some size reduction, while medium damaged samples did not. Severe damaged samples at 11 and 19 % moisture content had similar regression slopes but different intercepts, with the low moisture content samples (11 percent) having the higher intercept. The same trend could be observed for the medium damaged samples. This shift in bulk density was primarily due the effect of water added to increase moisture content from 11 to 19 %. This relationship showed that bulk density might be helpful in measuring mechanical damage for severe damaged samples but may not help in measuring mechanical damage for medium damaged samples. The correlation showed that bulk density does not necessarily correlate well with mechanical damage for different damage types. Size distribution of medium damaged and severe damaged samples was also obtained as shown in figure 3.15.

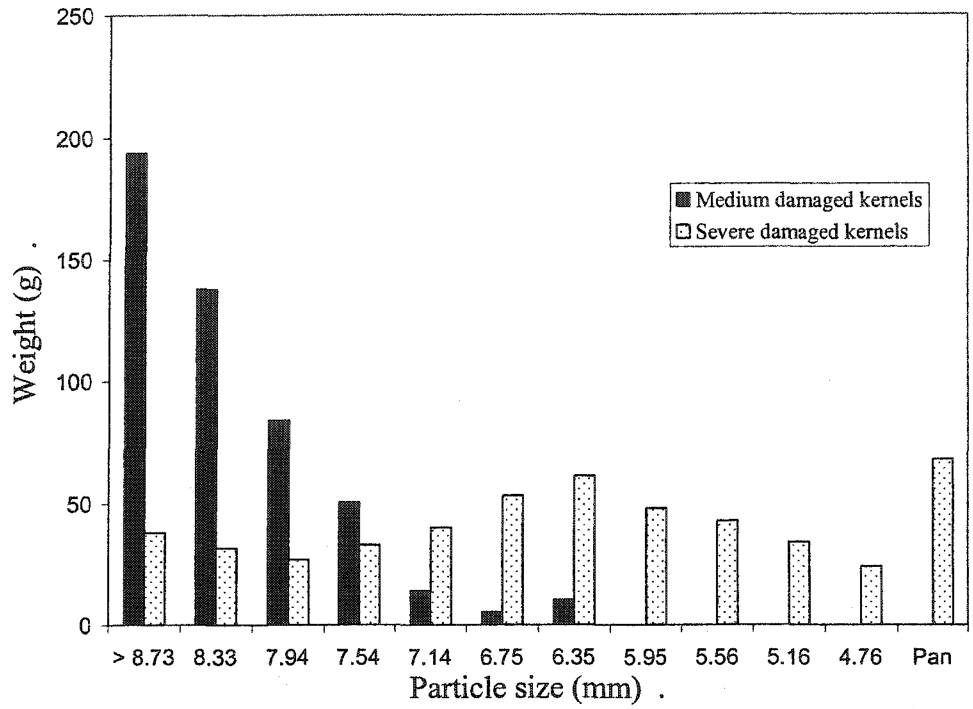

Figure 3.15. Size distribution of medium and severe damaged corn samples.

Dielectric properties

Preceding multivariate statistical analysis, dielectric constant and loss factor were plotted against measurement frequency for each type of mechanical damage to identify any separation among the different levels of mechanical damage. Dielectric properties of medium damaged corn at 11 percent moisture content are shown in figure 3.16. Each curve represents the average dielectric response of five replicates associated with each treatment. The dielectric constant values and the dielectric loss factors were plotted against the measurement frequencies. A decrease in dielectric constant with increase in damage level was observed. This was more obvious at the lower frequencies (below 10 kHz) than at the higher frequencies (above 10 kHz), which suggested that the dielectric constant at lower frequencies had the ability to describe mechanical damage more clearly than at higher frequencies. For dielectric loss factor, less variation with damage level existed at frequencies between 1 kHz and 10 kHz. At higher frequencies it did not show enough variation with damage level, although the bulk density values associated with the different mechanical damage levels were different. It was observed that variation among samples in bulk density did not appear to explain all the variation in dielectric properties with damage level. For example, although samples with 10 and 50 % damage level had the same bulk density (0.78 g/cm^3), the 10 % damage had a higher values of dielectric constant and loss factor than the 50 % damage. This variation was most probably due to the variation in damage level since moisture content and temperature were the same.

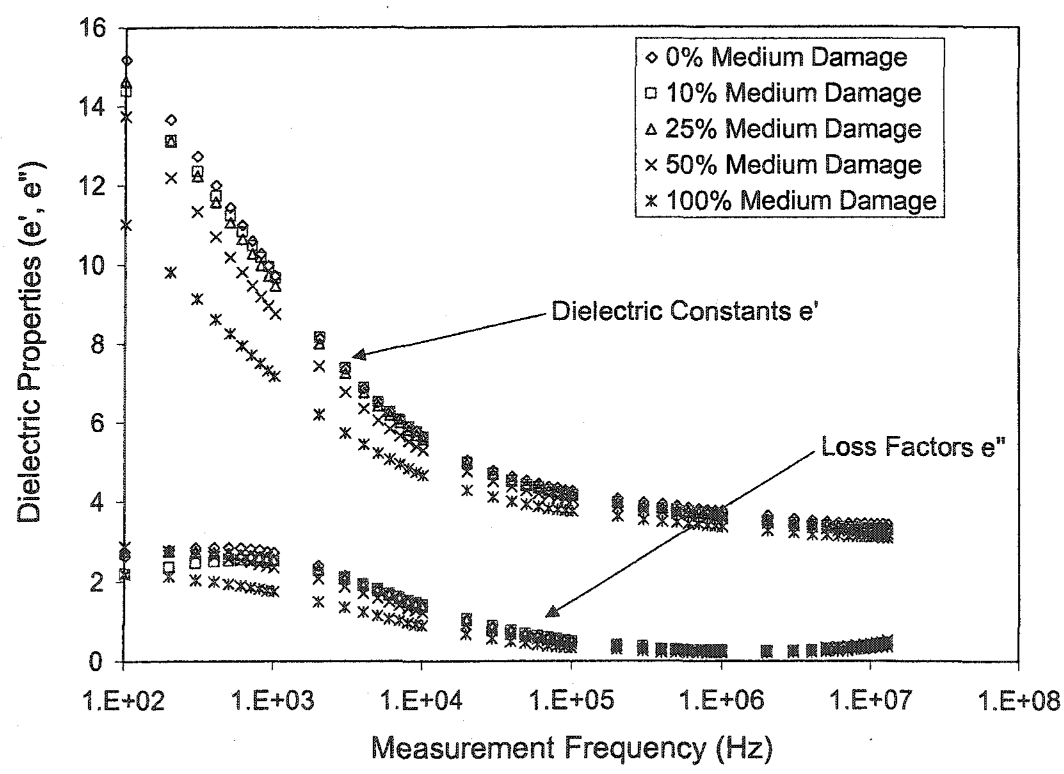

Figure 3.16. Dielectric constant and loss factor for medium damage levels at 11 % MC.

The plot shows that both dielectric constant and loss factor decreased as damage level increased. A similar plot for severe damage samples at 11 percent moisture content is shown in figure 3.17. The graph shows a decrease in dielectric constant with increase in percent mechanical damage. The difference between dielectric constant values for different levels of damage level was apparently higher than that associated with medium damage as a result of bulk density effect. Therefore, it was concluded that the decrease in dielectric constant with decrease in damage level was due to the net effect of both bulk density and mechanical

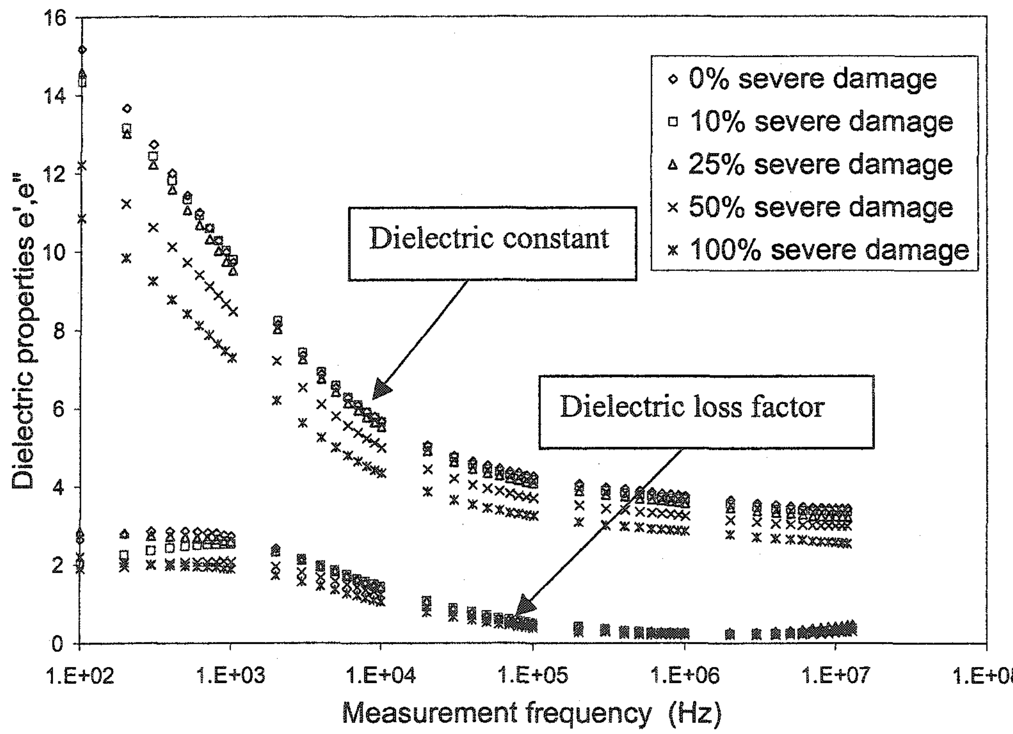

Figure 3.17. Dielectric constant and loss factor for severe damage levels at 11% MC.

damage level. For the dielectric loss factor, a similar trend was observed with less variation among the different damage levels associated with each sample compared to the variation in dielectric constant. The magnitude of separation among the different levels of mechanical damage appeared to decrease as the measurement frequency increased similar to the medium damaged samples.

Next, similar plots of dielectric properties versus measurement frequency were obtained at 19 % moisture content. The relationship between damage level and dielectric properties of the medium and severe damaged corn samples at 19 % moisture content is shown in figure 3.18 through 3.21. A log-log scale was used in order to describe the data points more clearly, since both dielectric constant and loss factor increased exponentially

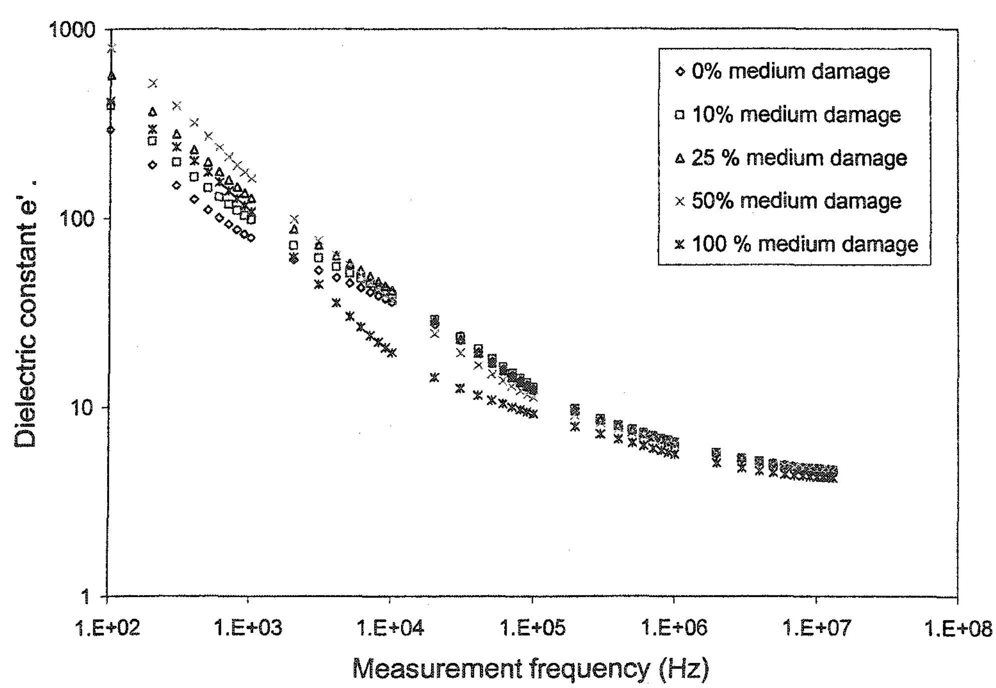

Figure 3.18. Dielectric constant for medium damaged corn at 19 % MC.

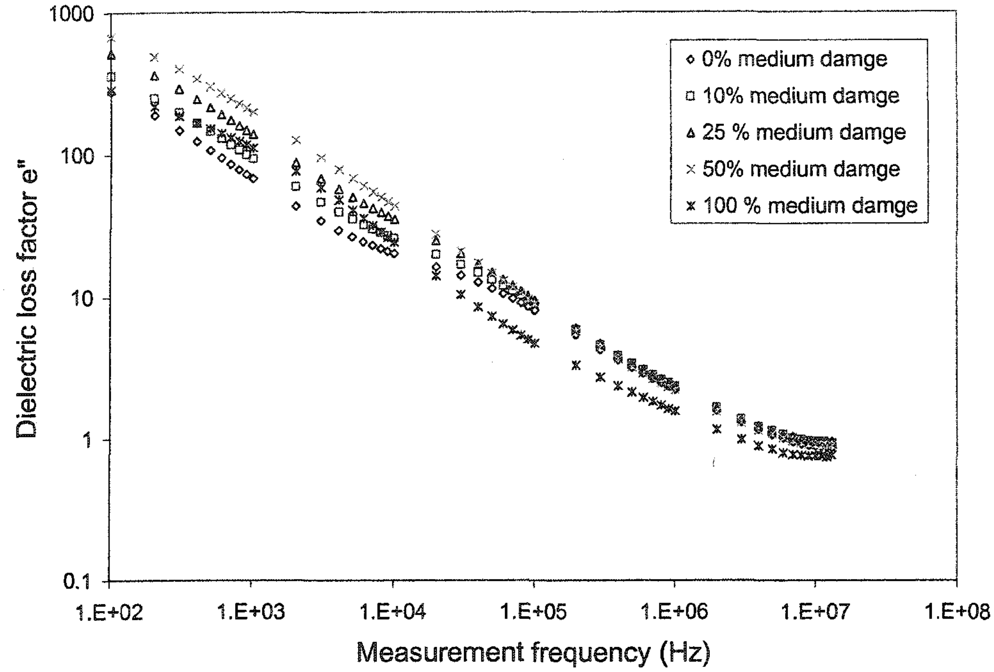

Figure 3.19. Dielectric loss factor for medium damaged corn at 19 % MC.

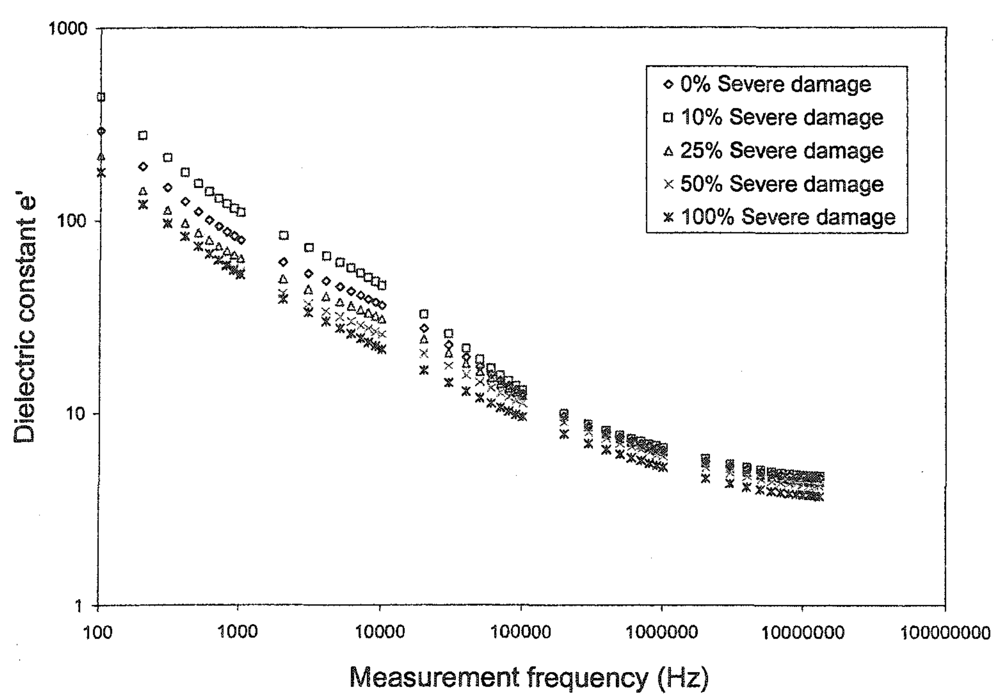

Figure 3.20. Dielectric constant for severe damaged corn at 19 % MC.

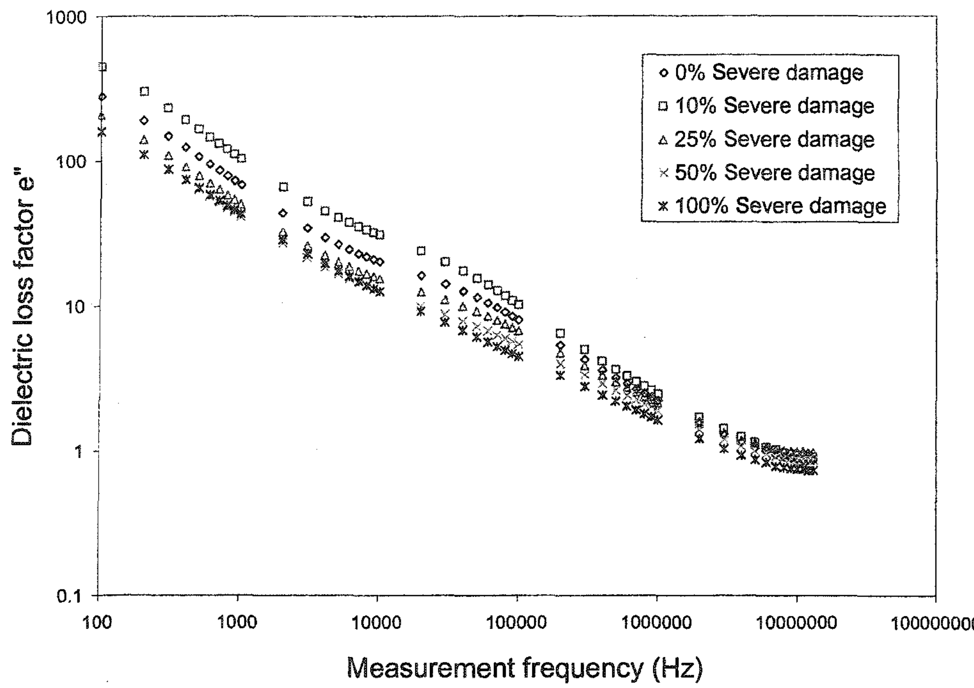

Figure 3.21. Dielectric loss factor for severe damaged corn at 19 % MC.

with the increase in moisture content from 11 to 19 %. Normally, the dielectric constant is higher than the loss factor for moist grain, but the two parameters appeared to overlap at the lower frequency range with the dielectric constant still slightly larger. This was mainly due to the effect of ionic conductivity, which was more dominant at lower frequencies and decreased as frequency increased. The dielectric loss factor at lower frequencies represented a combination of ionic and dielectric loss components and is usually denoted as the effective loss factor. The results showed that for medium damage, dielectric constant increased with increase in damage level except for 100 percent damage, which had values between the 25 and 50 % damage levels. The bulk density of the 100 percent damaged samples was similar to that of the 0 and 10 % damage while bulk density for the 25 and 50 % damage were higher. This suggested that the effect of bulk density decreased the value of dielectric constant for the 100 % damage level while the effect of damage tended to increase it. Therefore, the net result, was that dielectric constant for the 10 % damage level fell between the values for 25 and 50 % damage. It was also clear that samples with 0 and 10 percent damage had different dielectric constant although they had the same bulk density (0.70 g/cm^3). Dielectric loss factor showed an improvement in differentiating among the damage levels at the 19 % moisture content compared to its values at 11 % moisture content, especially at the lower frequencies. For severe damage at 19 % MC a decrease in the dielectric constant and loss factor with the increase in damage percent were observed (figure 3.19). It also showed that dielectric properties at 10 % damage level had higher values, than at 0 % damage level. This could be explained by the higher bulk density associated with the samples at 10 % damage level compared to the bulk density of the 0 % damage level. Although this difference in bulk density was not large, it tended to amplify itself at lower frequencies and higher moisture contents. Dielectric loss factor followed a similar trend also. These results showed that the moisture content effect on dielectric properties of corn was the most significant, then came the effect of bulk density and mechanical damage level. Therefore, it would be necessary to develop a method to compensate for the effect of moisture content and bulk density before making attempts to predict mechanical damage. Visual comparisons among the different levels of mechanical damage were helpful to understand the contribution of moisture content, bulk density, and mechanical damage level to the dielectric response. However, a more objective method of analysis was needed to help better understand the magnitude of contribution inflicted by each of these factors.

Statistical analysis

Analysis of Variance (ANOVA) for the damage data was performed using SAS proc mixed (SAS 1999). The dielectric constant and loss factors at every fifth measurement frequency were used as the response variable, and the corresponding moisture content, bulk density (compression), and mechanical damage were used as the predictor variables. An example of the results for the dielectric constant at 600 Hz (the 15^{th} measurement frequency) is shown in tables 3.1.

The table suggested that all three treatments, moisture content (MC), damage level (Damage%), and bulk density (Compression), were highly significant. It was observed also that the blocks (replicates) were insignificant, indicating low measurement errors. The table shows also that compression (bulk density), moisture content, and their interaction had much higher F values compared to damage percent. In other words, they had a higher effect on dielectric response compared to damage level. This suggested again that a good compensation for moisture content and bulk density effects would be necessary to develop the damage level prediction models. Since mechanical damage was found to have a

Table 3.1. Results of analysis of variance for dielectric constant at 600 Hz (15^{th} frequency) for medium damaged samples using SAS Proc Mixed.

Effect	Num DF	Den DF	F Value	Pr > F
Block	4	4	0.97	0.5125
MC	1	4	1033.57	<.0001
Damage%	4	32	17.92	<.0001
MC*Damage%	4	32	18.23	<.0001
Compression	1	40	1312.02	<.0001
Damage% *Compression	4	40	4.19	0.0063
MC*Compression	1	40	1295.55	<.0001
MC*Damage%*Compression	4	40	4.12	0.0069

significant effect on dielectric response, the next question was whether the different levels of mechanical damage were significantly different from each other. A least significant difference of means test between the different levels of mechanical damage was performed. The results are shown in table 3.2 for the same example measurement frequency used in table 3.1. The table shows a comparison between every two damage level combinations. All means were significantly different from each other at 5 percent level except for the 10 and 100 percent damage level pair. This could be the result of the density effect. In general, the results showed statistically significant differences among the different levels of mechanical damage, which further supported the possibility of using dielectric measurements for developing a mechanical damage sensor. Further analysis of dielectric constant and loss factor at frequencies other than 600 Hz showed similar results except at higher frequencies

Table 3.2. Least significant difference of means between damage levels for medium damaged samples using dielectric constant at 600 Hz.

LSD comparison Pair		Statistical parameters		
Level 1	Level 2	Estimate[§]	t value	Pr > |t|
0	10	-22.6	-2.35	0.0253
0	25	-54.5	-5.66	<.0001
0	50	-74.3	-7.71	<.0001
0	100	-29.4	-3.05	0.0046
10	25	-31.9	-3.31	0.0023
10	50	-51.7	-5.36	<.0001
10	100	-6.8	-0.70	0.4875
25	50	-19.8	-2.05	0.0486
25	100	25.1	2.61	0.0137
50	100	44.9	4.66	<.0001

[§] Degrees of freedom = 32 and standard error=9.6.

(above 1 MHz), where dielectric constant and loss factors were not able to detect the differences among the damage levels at the 5 percent level. The analysis was repeated for severe damaged samples and comparable results were obtained (data not shown).

The results obtained from both visual inspection and statistical analysis showed that dielectric properties had a good potential for detecting the differences among damage levels and therefore developing a fast technique for measuring mechanical damage level in corn samples. The dielectric response was also found to be affected by moisture content, bulk density (or material mass), and frequency. The only other factor that might obviously affect the dielectric response is temperature, which was maintained around the room temperature (21- 24 ^{0}C) throughout the experiment, and therefore, its effect was not included. The results suggest that both moisture content and bulk density had the majority of contribution to the dielectric properties and a proper compensation for the effect of those two factors should be considered before attempting to measure damage level. The nature of this compensation, however, should be further investigated due to the complexity of the dielectric response.

Next, the dielectric variables were used to develop a model for mechanical damage level prediction where each damage type was analyzed separately. Before, developing this regression model, however, the dielectric variables were screened to reduce the number of variables in the prediction models.

Variable selection and multivariate analysis

To screen the dielectric variables, principal component loadings associated with each dielectric variable were inspected for any influential observations using SAS Proc PCA (SAS, 1999). The loadings were very similar, however, due to multicollinearity (strong dependence among the dielectric variables) and this method was inefficient for screening the dielectric variables. Next, Multiple Linear Regression using SAS Proc MLR (SAS, 1999) option maxr was used. The results are shown in table 3.3. MLR procedure was used to find the best one to seven variables that maximize the coefficient of determination (R^2). The cut off level of significance was set to 5 %. The table shows the number of variables used in the damage level prediction model, with K, and M scripts denoting the frequency of the selected variables in kHz and MHz respectively. The corresponding coefficient of determination is also shown. A plot of R^2 against the number of variables selected is shown in figure 3.22. The figure shows that only two variables were needed to explain 91 percent of the variation in severe damage level, and that the improvement in R^2

Table 3.3. Variable selection using MAXR option for medium and severe damage.

Severe Damage		Medium damage	
Variables	R^2_s	Variables	R^2_m
1.$(\varepsilon'_{13M})^{1/3}$	**0.23**	ε'_{10k}	**0.08**
2.ε'_{3M}, $(\varepsilon'_{0.7M})^{1/3}$	**0.91**	$(\varepsilon'_{0.8k})^{1/3}$, $(\varepsilon''_{20k})^{1/3}$	**0.51**
3. ε'_{8M}, ε''_{11M}, $(\varepsilon'_{0.9M})^{1/3}$	**0.93**	$\varepsilon''_{0.4M}$, $(\varepsilon'_{0.8M})^{1/3}$,$(\varepsilon''_{20k})^{1/3}$	**0.58**
4. $\varepsilon'_{0.3M}$, ε'_{3M}, ε''_{11M} $(\varepsilon'_{0.9M})^{1/3}$	**0.95**	ε'_{90k}, $(\varepsilon'_{0.8k})^{1/3}$,$(\varepsilon''_{2M})^{1/3}$ $(\varepsilon''_{80k})^{1/3}$	**0.80**
5. ε'_{20k}, $(\varepsilon'_{5M})^{1/3}$,$(\varepsilon''_{0.09k})^{1/3}$ $\varepsilon'_{0.3M}$, ε''_{11M}	**0.96**	$\varepsilon'_{0.1M}$, $(\varepsilon'_{1k})^{1/3}$,$(\varepsilon'_{2M})^{1/3}$ $(\varepsilon''_{0.04})^{1/3}$,$(\varepsilon''_{80k})^{1/3}$	**0.84**
6. ε'_{60k}, ε'_{100k}, $\varepsilon''_{0.03k}$ $(\varepsilon'_{2M})^{1/3}$, $(\varepsilon''_{0.04k})^{1/3}$,$\varepsilon''_{0.3M}$	**0.97**	$\varepsilon'_{0.1M}$, $\varepsilon''_{0.03}$, $(\varepsilon''_{80k})^{1/3}$ $(\varepsilon'_{1k})^{1/3}$, $(\varepsilon'_{2M})^{1/3}$, $(\varepsilon''_{0.04})^{1/3}$	**0.88**
7. No Change		$\varepsilon'_{0.5M}$, $\varepsilon''_{0.04k}$, $\varepsilon''_{0.5M}$ $(\varepsilon'_{1k})^{1/3}$, $(\varepsilon'_{0.9M})^{1/3}$, $(\varepsilon''_{0.04k})^{1/3}$ $(\varepsilon''_{60k})^{1/3}$	**0.91**

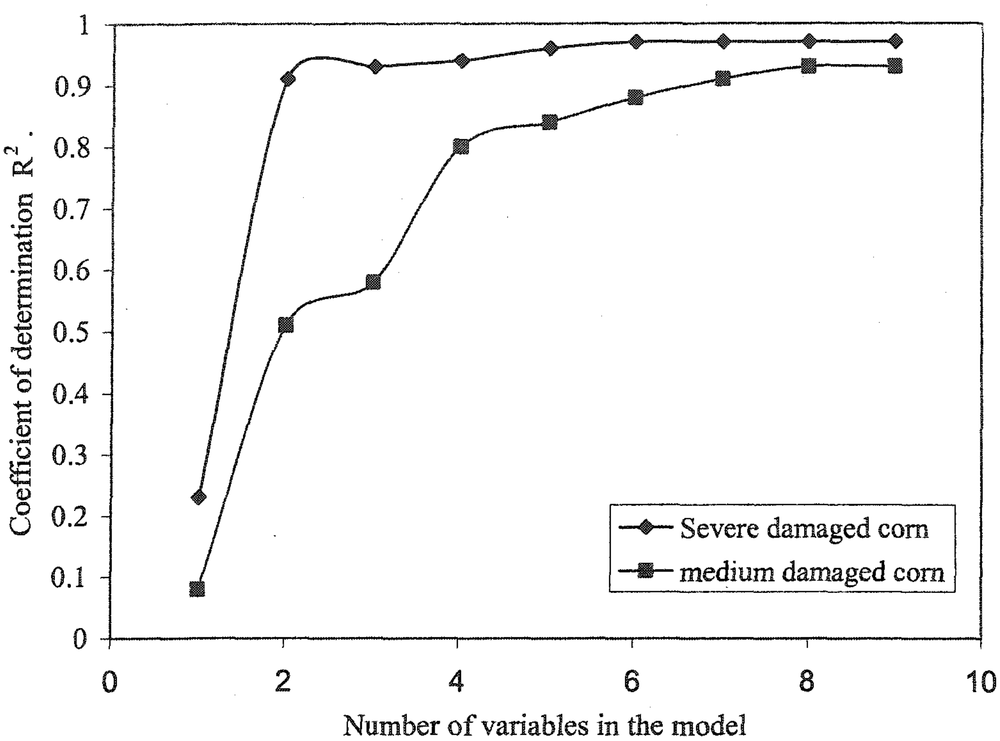

Figure 3.22. Coefficient of determination for the selected variables, for medium and severe damage using multiple linear regression.

beyond two variables was relatively small. On the other hand, seven variables were needed to explain 91 percent of the variation in medium damage level, which indicates that severe damage was easier to predict than medium damage

Mechanical damage calibration using dielectric variables only

The six-variable model for severe damaged samples was selected from table 3.3, since the improvement in R^2 beyond six variables was very small. Next, the selected variables were regressed on damage level using General Linear Model (SAS Proc GLM, SAS 1999). The model was then refined by eliminating any variable that was highly correlated with another variable in the prediction model. This resulted in a four-variable model. It was difficult to pre-specify which variables to remove, due to the fact that some degree of multicollinearity existed among all the dielectric variables. Multicollinearity was evaluated using the Variance Inflation Factor (VIF). A trial procedure was followed to select the dielectric variables by removing one variable at a time and observing the model performance. Using those four variables, analysis of variance for severe damaged corn samples was established using SAS proc GLM General Linear Model (SAS 1999). The results showed that all the main effects and their interactions were significant at $\alpha = 0.01$, therefore, the interactions were added to the model. The resulting coefficient of determination (R^2) was 0.97 and the root mean square error (RMSE) was 6.5 %. The predicted damage level observations were checked for statistical outliers, which were defined as observations with residuals outside the boundaries of three standard deviations. Only one outlier was detected. The original data were inspected and it was observed that the dielectric values associated with that observation were unusually low compared to other observations at similar conditions. Further investigation showed a dip in the dielectric measurements indicating a measurement error and the observation was removed. The regression was repeated, and the ANOVA is shown in table 3.4. The results showed a slight improvement with $R^2 = 0.98$ and RMSE = 5.97 %.

It was observed from table 3.4 that three of the four variables picked by the regression model were from the lower frequency range (40 Hz, 60 kHz, and 100kHz) and only one variable was picked from the higher frequencies (2 MHz). This agrees with the visual plots of dielectric variables against frequency explained earlier, which suggested that lower frequencies could be more sensitive to mechanical damage than higher frequencies.

Table 3.4. The results of ANOVA for severe damage level prediction using dielectric variables only.

Parameter[§]	Estimate	Std Err	t- Value	Pr > |t|
Intercept	1646.65	160.91	10.23	<.0001
A	-603.21	103.16	-5.85	<.0001
B	514.09	113.96	4.51	<.0001
A*B	-2.83	0.61	-4.67	<.0001
C	-1046.18	97.38	-10.74	<.0001
A*C	307.05	54.26	5.66	<.0001
B*C	-226.30	56.71	-3.99	0.0002
D	437.72	71.05	6.16	<.0001
A*D	-3.12	1.00	-3.11	0.0027
B*D	9.14	1.99	4.58	<.0001
C*D	-249.15	43.45	-5.73	<.0001

[§] $A = \varepsilon'_{60k}$, $B = \varepsilon'_{100k}$ $C = \varepsilon'_{2M}$, $D = (\varepsilon''_{0.04k})^{1/3}$

In order to understand the proportional contribution of moisture content and bulk density to damage prediction, the observations were grouped by moisture content and compression level (bulk density) and plotted in figure 3.23. The figure shows the density (compressed and uncompressed). The figure suggested that mechanical damage prediction was not affected by any particular moisture content and bulk density level over the others.

For medium damage corn samples, the seven-variable model was selected from table 3.3. The seven-variable model was selected since the increase in R^2 beyond seven variables was very small. Further refining of the model resulted in a reduction of the number of variables from seven to four. Next, analysis of variance was performed on the selected combination of high and low moisture content (11 and 19%), and the high and low bulk variables and a check for outliers was performed as before. Two outliers were detected and inspected. It was observed that the two observations had a lower dielectric properties

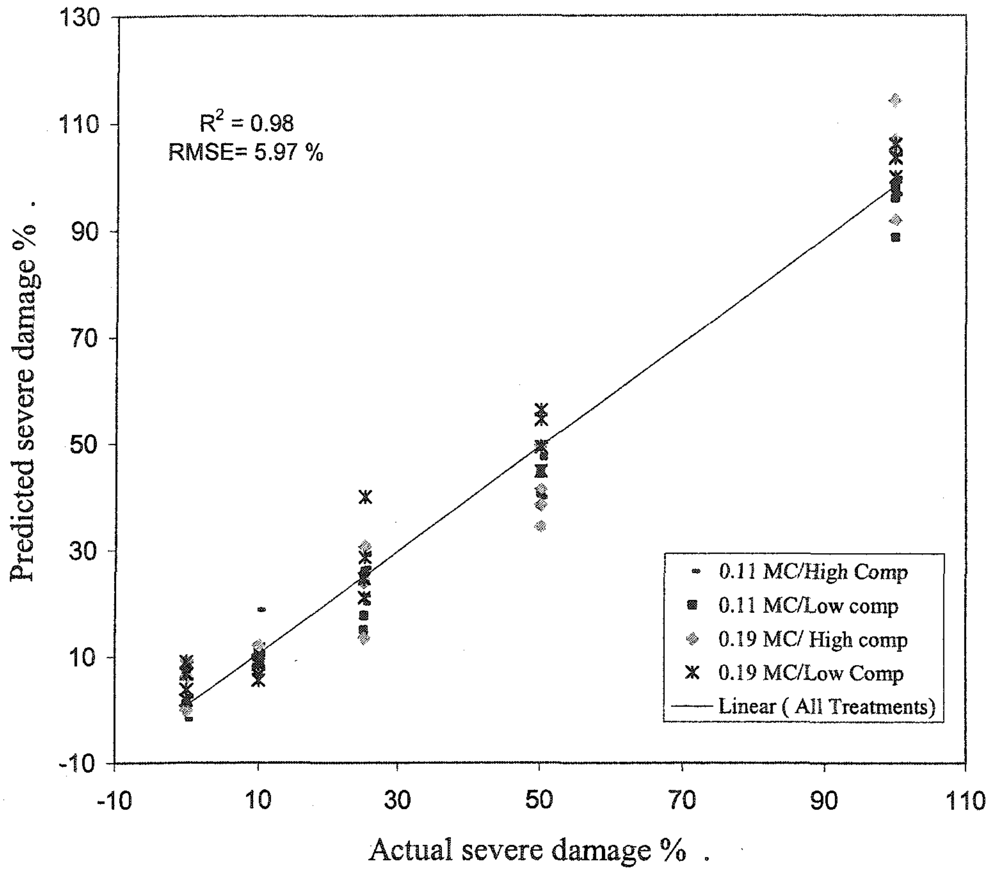

Figure 3.23. Predicted versus actual severe damage for all treatments using the four variable model (individual symbols represent different moisture content and bulk density combinations).

compared to similar observations due to an unexplained dip in the dielectric measurements. The two observations were excluded. Analysis of variance using the new four variables and their significant interactions is shown in table 3.5. After removing the outliers, the coefficient of determination increased from 0.91 to 0.95 and RMSE decreased from 11.2 to 8.8 percent. It was observed that medium damage level was harder to predict than severe damage level since four variables were used to predict medium damage level with $R^2 = 0.95$

Table 3.5. The results of ANOVA for medium damage level prediction using dielectric variables only.

Parameter§	Estimate	Std Err	t value	Pr > |t|
Intercept	6402.58	450.17	14.22	<.0001
A	331.96	31.82	10.43	<.0001
B	-0.84	0.09	-9.05	<.0001
C	47.40	7.93	5.98	<.0001
D	-4614.27	349.17	-13.22	<.0001
E	89.66	6.06	14.80	<.0001
F	-203.06	24.70	-8.22	<.0001
A*B§§	-6.16	0.00	-2.77	0.0072
A*E§§	52.10	0.01	8.17	<.0001
B*B§§§	-3.80	0.00	-5.96	<.0001

§A= ε'_{1M}, B = $\varepsilon''_{0.04k}$, C = $(\varepsilon'_{1k})^{1/3}$, D= $(\varepsilon'_{1M})^{1/3}$,
E= $(\varepsilon''_{0..04k})^{1/3}$, F = $(\varepsilon''_{80k})^{1/3}$
§§The parameter estimate is multiplied by 1E+03.
§§§ The parameter estimate is multiplied by 1E+05.

compared to $R^2 = 0.98$ using the same number of variables for severe damage. It is likely that severe damage levels were predicted more precisely due to the contribution of bulk density to the dielectric response. However, density variation alone was unable to explain the prediction improvement, since the dielectric properties of the corn samples were shown to respond to the variations in damage level as well. In addition, no good correlation was found between medium damage level and bulk density, yet the dielectric variables were able to predict damage level with a good accuracy level ($R^2 = 0.95$) and a RMSE = 8.8 %.

It was also observed that three variables were picked at the lower frequency range (40 Hz, 1 KHz, and 80 KHz) and only one variable was picked at higher frequency (1 MHz). This was similar to the trend observed with the severe damage prediction, although the frequencies were a little different. The dielectric loss factor at 40 Hz was picked for the model in both damage types, which suggested that a DC measurement of sample resistance might be helpful in predicting damage level. Next, a plot of the damage level prediction using the four combinations of moisture content and compression level similar to the one developed for severe damaged samples was obtained as shown in figure 3.24. The plot shows those predicted observations grouped by the combinations of low compression with 0.11 and 0.19 moisture content, and high compression with 0.11 and 0.19 moisture content. The figure

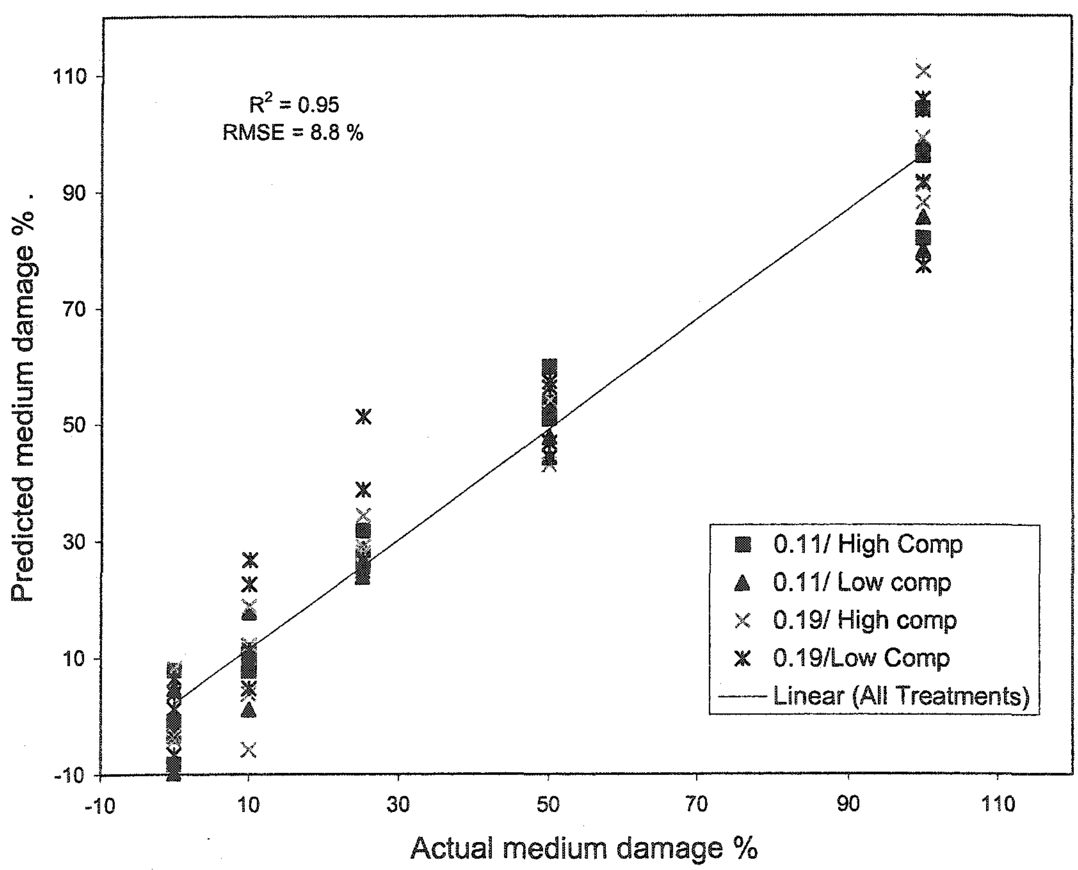

Figure 3.24. Predicted versus actual medium damage for all treatments using the four variable model (individual symbols represent different moisture content and bulk density combinations).

suggested again that damage level prediction did not respond to a certain moisture content and compression level combination more than the other combinations. The previous discussion showed that it was possible to predict damage level for medium and severe damaged corn samples using dielectric variables only, however, the prediction model had to account for the effect of moisture content and bulk density first; since the two variables were found to have a major effect on the dielectric response of the corn samples. Therefore, it was assumed that the prediction model accounted for the effect of moisture content and bulk density on dielectric variables without using those two parameters in the prediction model explicitly. This was verified by regressing the moisture content and bulk density on the dielectric variables used in the damage prediction model developed above. For severe damage, the moisture content was predicted using three of the four variables used in the damage level prediction with R^2 = 0.99 and RMSE = 0.01 (ε''_{40Hz} was omitted from the model) and bulk density was predicted using the same three variables with R^2 = 0.99 and RMSE = 0.007 g/cm^3. For medium damage, the moisture content was predicted with R^2 = 0.99 and a RMSE = 0.006 using only three of the four variables used in medium damage prediction ($(\varepsilon''_{80KHz})^{1/3}$ was omitted from the model), and the bulk density was predicted with R^2 = 0.95 and a RMSE = 0.009 g/cm^3 with all four variables used in the damage level prediction retained by the model. These results suggested that moisture content and bulk density were well accounted for in the damage level prediction model.

Next, the moisture content and bulk density, were used explicitly in the damage level prediction model to investigate the possibility of improving damage prediction accuracy or decreasing the number of dielectric variables used in the model.

Mechanical damage calibration using moisture content, density, and dielectric properties

Moisture content and bulk density were shown to have a large effect on the dielectric properties of damaged corn. Therefore, it might be useful to compensate for those two parameters explicitly in the damage prediction equation, in order to improve the prediction model. Two different approaches were used. In the first one, the actual moisture content and bulk density (oven-measured moisture content, and standard test weight) were used in the prediction equation along with dielectric variables. In the second one, moisture content and bulk density were predicted using dielectric properties, then the predicted values were used in damage level prediction model along with the dielectric variables.

Actual moisture content and bulk density were used along with dielectric properties to improve damage level prediction. For severe damage prediction, the addition of actual moisture content and bulk density reduced the number of dielectric variables needed from four to two. The final results are shown in table 3.6. The accuracy of prediction declined slightly, however, with R^2 = 0.97 and RMSE = 6.96 percent compared to R^2 = 0.98 and RMSE = 5.97 when using four dielectric variables alone. For medium damage prediction using actual moisture content, bulk density, and dielectric variables, the results are shown in table 3.7. The actual bulk density, actual moisture content, and four dielectric variables at three frequencies were used. The regression model showed an improvement in prediction accuracy of medium damaged corn samples when the actual moisture content and bulk density were introduced to the regression with an increase in R^2 from 0.95 to 0.98 and a decrease in RMSE from 8.8 to 5.77 percent. The number of the dielectric variables did not decrease, although the four variables used represented three frequency measurements only ($\varepsilon''_{0.1KHz}$, $(\varepsilon'_{0.1KHz})^{1/3}$, ε''_{80KHz} , and ε'_{10KHz}). This reduced the number of frequencies needed from four to three. The frequencies picked up by the regression model for both damage types were less than 100 kHz, which agreed with the earlier findings that lower frequency measurements were able to distinguish among the different levels of corn mechanical damage better than higher frequency measurements. The results showed, that damage prediction model based on the dielectric variables alone was able to account for the majority of moisture content and bulk density effect. This was evident from the slight improvement in prediction

Table 3.6. Severe damage prediction using actual moisture content, bulk density, and dielectric variables.

Parameter§	Estimate	Std Err	t-value	Pr >|t|
Intercept	656.07	26.24	25.00	<.0001
A	-0.16	0.04	-3.75	0.0003
B	36.79	5.05	7.28	<.0001
C	-148.31	17.44	-8.50	<.0001
Density	-635.59	28.15	-22.58	<.0001
MC	-745.65	179.09	-4.16	<.0001
A*C	0.04	0.01	3.31	0.0014

§ $A = \varepsilon''_{0.03K}$, $B = (\varepsilon''_{0.03K})^{1/3}$, $C = \varepsilon''_{90K}$, MC = standard oven method, Density = standard test weight.

Table 3.7. Medium damage prediction using actual moisture content, bulk density, and dielectric variables.

Parameter§	Estimate	Std Err	t-value	Pr >|t|
Intercept	336.66	339.14	0.99	0.3244
A	47.94	3.26	14.72	<.0001
B	-111.64	8.45	-13.21	<.0001
C	61.52	19.47	3.16	0.0024
D	-1345.58	129.40	-10.40	<.0001
Density	3926.49	472.02	8.32	<.0001
MC	9017.24	2624.17	3.44	0.001
Density*MC	-37421.39	3825.26	-9.78	<.0001
B*Density	130.52	12.76	10.23	<.0001
A*MC	-252.23	17.15	-14.71	<.0001
C*MC	-306.13	102.46	-2.99	0.0039
D*MC	7257.89	681.27	10.65	<.0001

§ $A = \varepsilon''_{0.1K}$, $B = \varepsilon''_{80K}$, $C = \varepsilon'_{10K}$, $D = (\varepsilon'_{0.1K})^{1/3}$

accuracy when the actual moisture content and bulk density were introduced to the severe damage prediction model. Introducing actual moisture content and bulk density has clearly improved medium damage prediction with R^2 increasing from 0.95 to 0.98 while severe damage prediction was not significantly improved. Predicted versus observed medium damage level using this model was plotted as shown in figure 3.25. The figure shows a better prediction of medium damage level using the actual moisture content, bulk density, and dielectric variables compared to dielectric variables alone. The model performance has improved due to introducing some significant interactions. In order to check for the validity

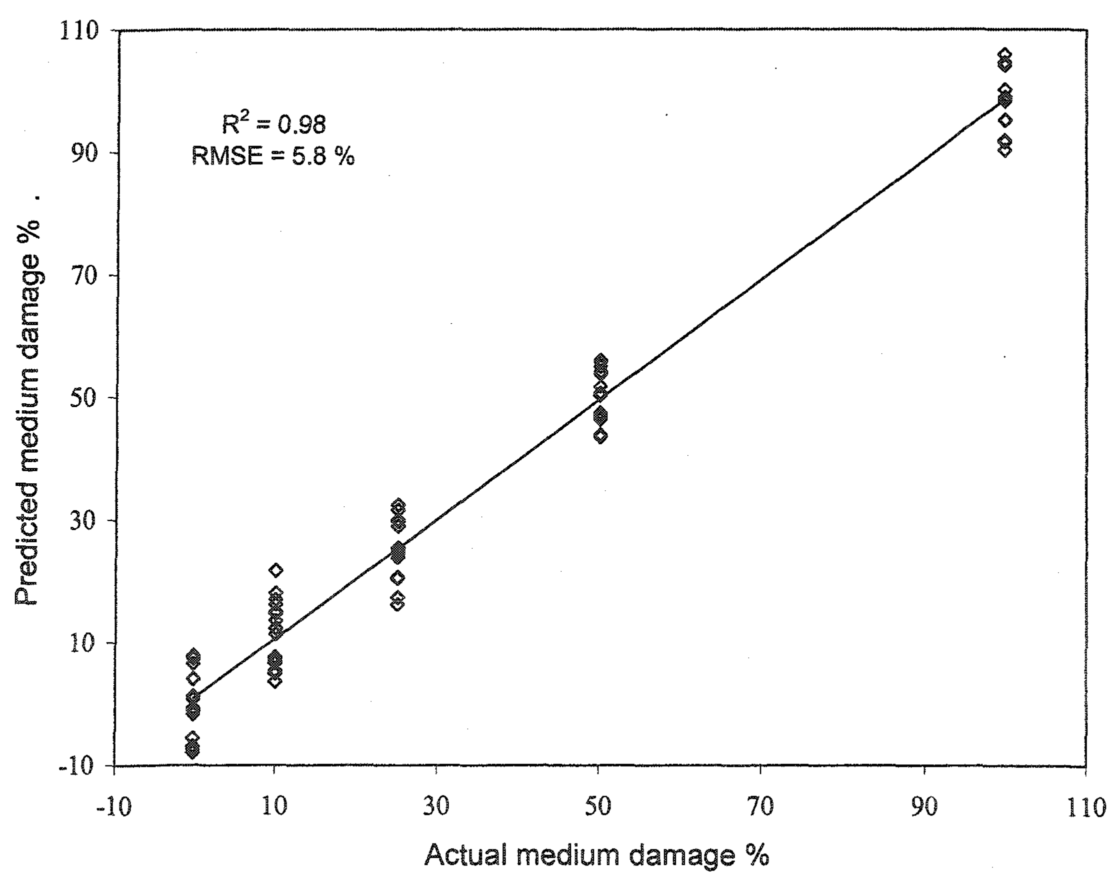

Figure 3.25. Medium damage level prediction using actual moisture content, bulk density, and dielectric variables.

of those interactions, both the t-values and the plots of those interactions were examined. No interactions were observed. Next, bulk density and moisture content were predicted using dielectric variables and the predicted values were used to replace actual moisture and bulk density in the damage level prediction model.

Mechanical damage calibration using predicted moisture content, predicted density, and dielectric properties.

Moisture content for corn samples was also predicted using dielectric properties for all corn samples (severe, and medium damage). A prediction model using a one and two-dielectric variable was developed as follows:

<u>One-variable</u>: $MC = -0.12 + 0.123(\varepsilon'_{0.2M})^{1/3}$, $R^2 = 0.96$

<u>Two-variable</u>: $MC = 0.0838 + 0.346(\varepsilon'_{0.4M})^{1/3} - 0.338(\varepsilon'_{3M})^{1/3}$, $R^2 = 0.99$

Bulk density of corn samples was also predicted using all corn samples using a two, three, and four dielectric variable model as follows:

<u>Two-variable</u>: $BD = 0.346 - 0.084(\varepsilon'_{0.4M}) + 0.156\,(\varepsilon'_{3M})$, $R^2 = 0.91$

<u>Three-variable:</u> $BD = -0.676 - 0.866(\varepsilon'_{0.4M})^{1/3} - 0.105\,(\varepsilon''_{0.4M})^{1/3} + 1.709(\varepsilon'_{3M})^{1/3}$, $R^2 = 0.95$

<u>Four-variable</u>: $BD = -0.708 - 0.963(\varepsilon'_{0.4M})^{1/3} - (\varepsilon''_{0.4M})^{1/3} + 1.793\,(\varepsilon'_{3M})^{1/3} + 0.128(\varepsilon''_{3M})^{1/3}$, $R^2 = 0.96$

The two-variable moisture content model with $R^2 = 0.99$ and RMSE = 0.004 and the Three-variable model for bulk density with $R^2 = 0.95$ and RMSE = 0.011 were selected. The results are shown in figure 3.26, and 3.27.

Medium damage prediction was improved by introducing the actual moisture content and bulk density to the prediction model along with the dielectric variables. It was found also that moisture content and bulk density were predicted quite accurately using dielectric

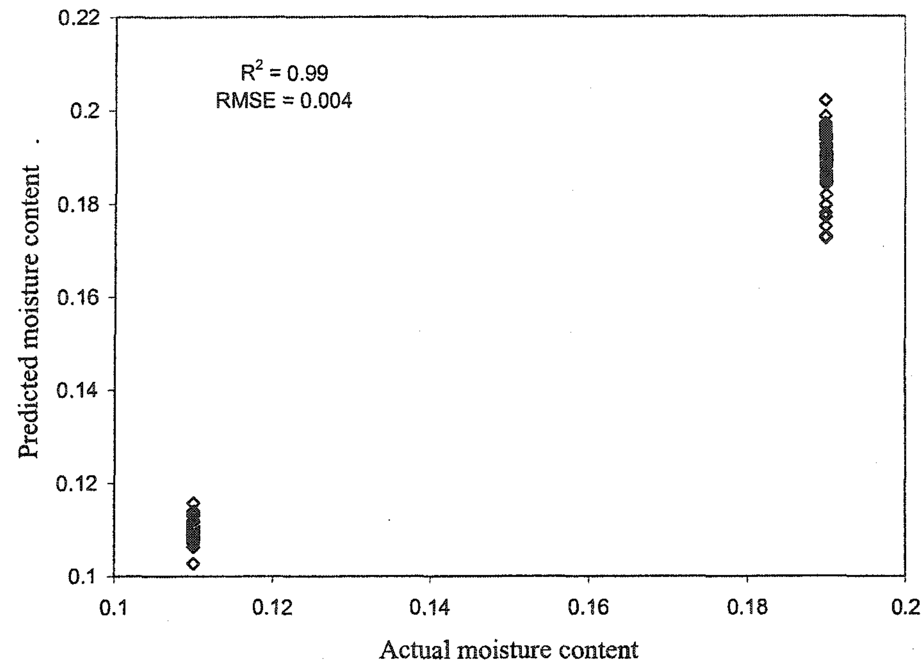

Figure 3.26. Predicted versus actual moisture content for both types of damage using dielectric variables.

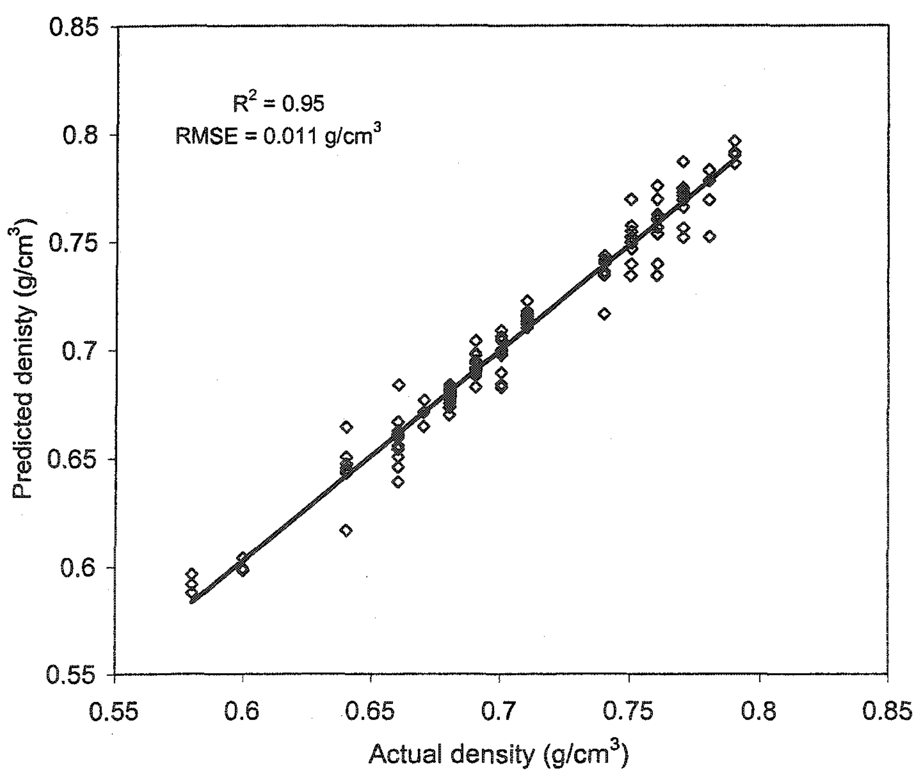

Figure 3.27. Predicted versus actual bulk density for both types of damage using dielectric variables.

properties. Therefore, in an attempt to develop a better prediction of medium and severe damage level using dielectric variables only, the predicted values of moisture content, and bulk density were used in the place of actual moisture content and bulk density, and the regression was performed again. The results showed that the performance of prediction for both types of damage deteriorated substantially. The new R^2 value decreased to 0.74 (the results are not shown). It can be concluded, therefore, that the best prediction for medium damage was obtained using a combination of the actual moisture content, bulk density, and dielectric variables, while for severe damage, damage prediction based on dielectric variables alone or based on the actual moisture content, actual bulk density, and dielectric variables was useful. The results are summarized in table 3.8.

Table 3.8. Summary of prediction results for artificial corn mechanical damage.

	Severe damage			Medium damage		
Model used	Variables	R^2	RMSE	Variables	R^2	RMSE
Dielectric variables	4	0.98	5.97	4	0.95	8.80
Dielectric variables and actual bulk density and MC	2	0.97	6.96	4	0.98	5.77
Dielectric Variables and predicted bulk density and MC		Poor			Poor	

Combine mechanical damage

Mechanical damage level (percentage) was evaluated using quantitative visual inspection and Chowdhury's method. The results for the four damage levels used in the experiment are shown in table 3.9. The results are shown as percentage ratio of damaged to undamaged corn weight for the combine-harvested corn samples. The table shows that mechanical damage measurements using visual inspection resulted in higher values of damage percentage compared to the measurements obtained from Chowdhury's method. This is to be expected since the visual inspection method accounted for all visually types of damaged corn kernels from chops to hairline scratches, while Chowdhury's method detected the damaged kernels with exposed starchy parts only. Chowdhury's test is faster, more precise, and less subjective than visual inspection method. Fines and splits, that passed through a 4.76 mm (12/64 in) round-hole sieve were excluded from the analysis, since the

Table 3.9. Corn mechanical damage evaluation using quantitative visual inspection method and Chowdhury's method.

Damage level	sample weight (g)		fines %	Mechanical damage %	
				visual	Chowdhury
No damage	250		0.00	0.00	0.00
	250		0.00	0.00	0.00
	250		0.00	0.00	0.00
		Mean	**0.00**	**0.00**	**0.00**
		Std Dev	**0.00**	**0.00**	**0.00**
Level 1	250		0.80	12.10	6.00
	250		0.60	10.00	7.00
	250		0.50	9.60	5.70
		Mean	**0.60**	**10.60**	**6.20**
		Std	**0.15**	**1.34**	**0.68**
Level 2	250		1.40	16.90	8.70
	250		1.80	17.00	7.70
	250		2.30	18.20	9.00
		Mean	**1.80**	**17.40**	**8.50**
		Std	**0.45**	**0.72**	**0.68**
Level 3	250		6.50	30.70	12.70
	250		6.20	30.60	13.70
	250		8.90	32.40	15.00
		Mean	**7.20**	**31.20**	**13.80**
		Std	**1.48**	**1.01**	**1.15**

damaged sample used in obtaining dielectric measurements excluded this fraction. In field operations during harvest, most of this portion is usually blown away by the combine fan. The relationship between Chowdhury test and visual inspection test is shown in figure 3.28.

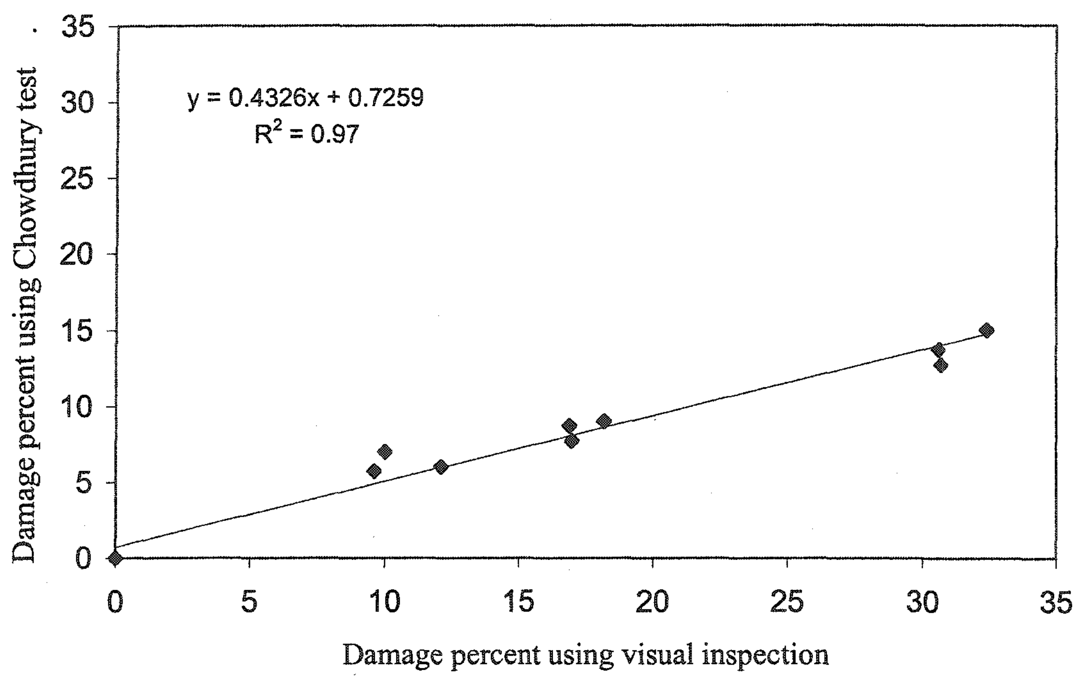

Figure 3.28. The relationship between Chowdhury and visual inspection damage level tests.

The graph shows a strong correlation between the two tests, although damage level measured by Chowdhury's method appeared to underestimates damage level measured by quantitative visual inspection method. Both damage level measurement methods (Chowdhury test, and visual inspection)were used as the reference measurements for developing the calibration model for mechanical damage using dielectric properties.

Bulk density and mechanical damage

The relationship between bulk density and mechanical damage using visual inspection is shown in figure 3.29. The figure shows bulk density against mechanical damage for compressed and uncompressed corn samples at the three levels of moisture content used in the experiment: 12.5, 18 and 23 percent. It shows that bulk density decreases with increase in mechanical damage percent for samples at 12.5 percent moisture content as inflicted by the small negative slope, however, it shows a slight increase in bulk density with mechanical damage at 18 and 23 percent moisture content as observed from the small positive slope. Statistical analysis showed, however, that none of the three lines had slopes significantly different from zero at α =0.05. Therefore, the relationship between bulk density and damage percent would not be useful for predicting damage level for this set corn samples. It was

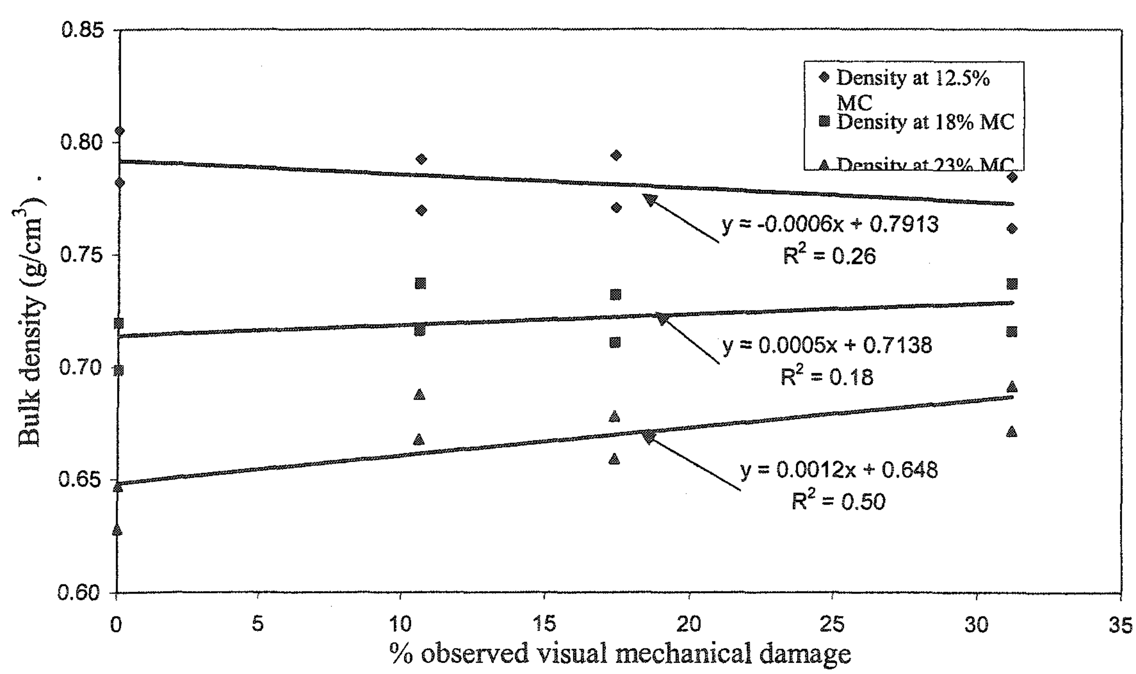

Figure 3.29. Bulk density for combine mechanical damaged samples.

observed from the same figure also, that the first damage level (10.6 percent) had a higher bulk density than the second damage level (17.6 percent), which indicated that the two damage levels were not different from each other, although damage evaluation tests using visual inspection and Chowdhury's method suggested that they were different by a magnitude of 6.8 and 2.3 percent respectively. The bulk density for each of the two damage levels was rechecked and the results confirmed that the 10.6 percent damage level were higher than the 17.6 percent damage level.

Dielectric properties

The plots of dielectric constant and loss factor against the measurement frequency were helpful in understanding the contribution of damage level, moisture content, and bulk density to the dielectric response of the corn samples fro artificially damaged corn samples. A similar analysis was performed for combine damaged corn samples. The experimental design included three moisture contents (12.5, 18, and 23 %) at two different bulk densities (compression levels). A separate plot for each combination of moisture content and compression level was performed. Examples of these plots are shown in figures 3.30 and 3.31. Figure 3.30, shows the dielectric constant for uncompressed damaged corn samples at 0.125 moisture content and Figure 3.31 shows the dielectric loss factor for uncompressed damaged corn samples at 0.125 moisture content. The figures showed the four damage levels and their associated bulk densities. Bulk density was shown for each damage level because of the variations in its values for the different damage levels. The dielectric response shown in the plot was essentially the net effect of the two variables, damage level and bulk density. It was observed that dielectric constant decreased as damage level increased. Again, lower increase, especially at lower frequency measurements.

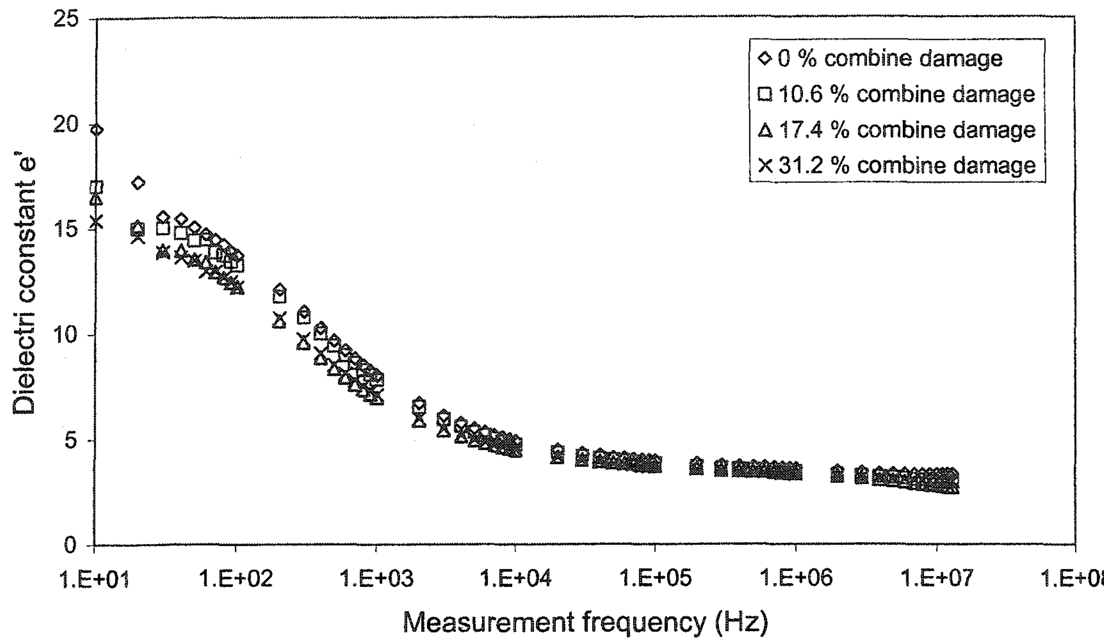

Figure 3.30. Dielectric constant for 12.5 % MC, uncompressed samples.

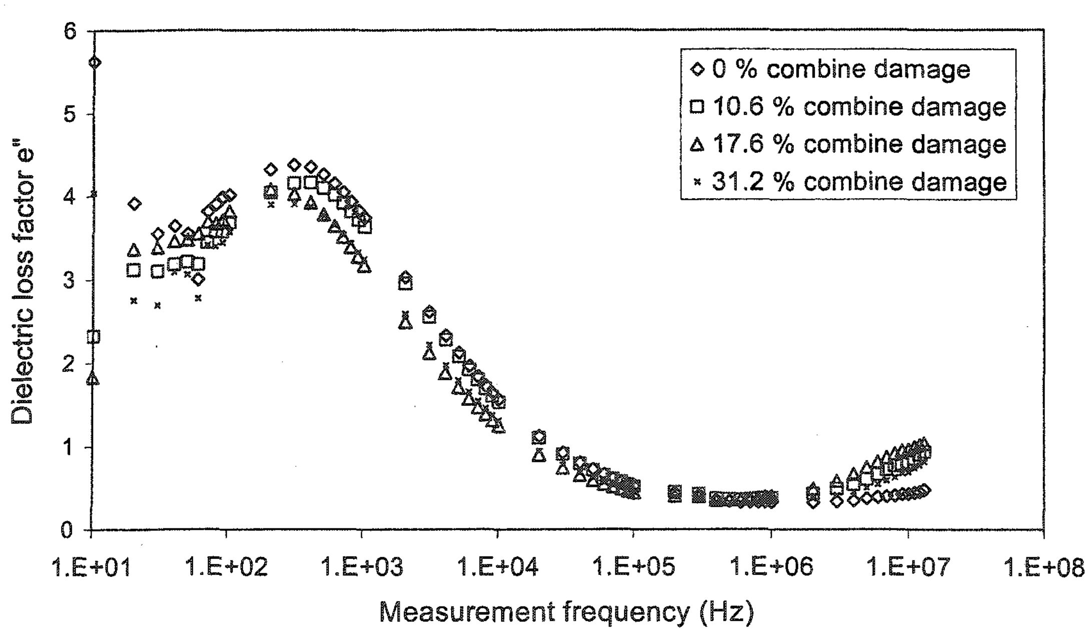

Figure 3.31. Dielectric loss factor for 12.5 % MC, uncompressed samples

Frequency measurements were able to show a better separation among damage levels in the lower frequency range than at the higher frequency range. Dielectric loss factor showed a decrease with damage level zero percent mechanical damage rather than with the highest damage level (31%). Therefore, the dielectric response of the samples was viewed as the net result of bulk density and mechanical damage effect, provided that moisture content was fixed. Next, similar plots of dielectric constant and loss factor responses at the intermediate moisture content (18 %) were obtained as shown in figure 3.32 and 3.33. Figure 3.32 shows the dielectric constant of each damage level. It was observed that dielectric constant increased as damage level increased at measurement frequencies below 1 kHz, while dielectric constant for the undamaged corn sample switched it's location to become higher

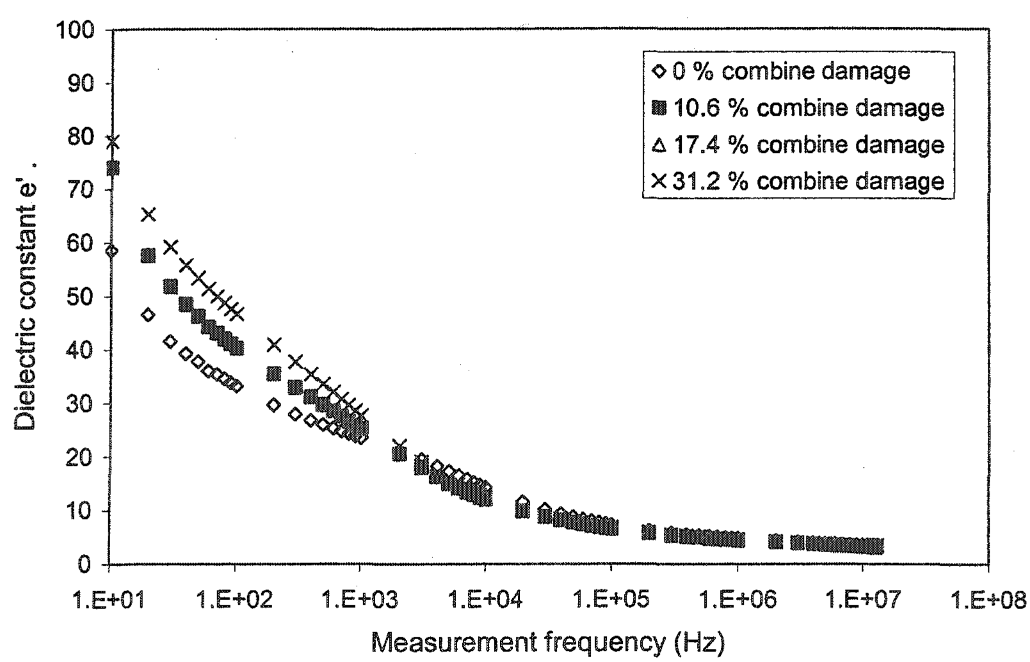

Figure 3.32. Dielectric constant for 18 % MC, uncompressed samples.

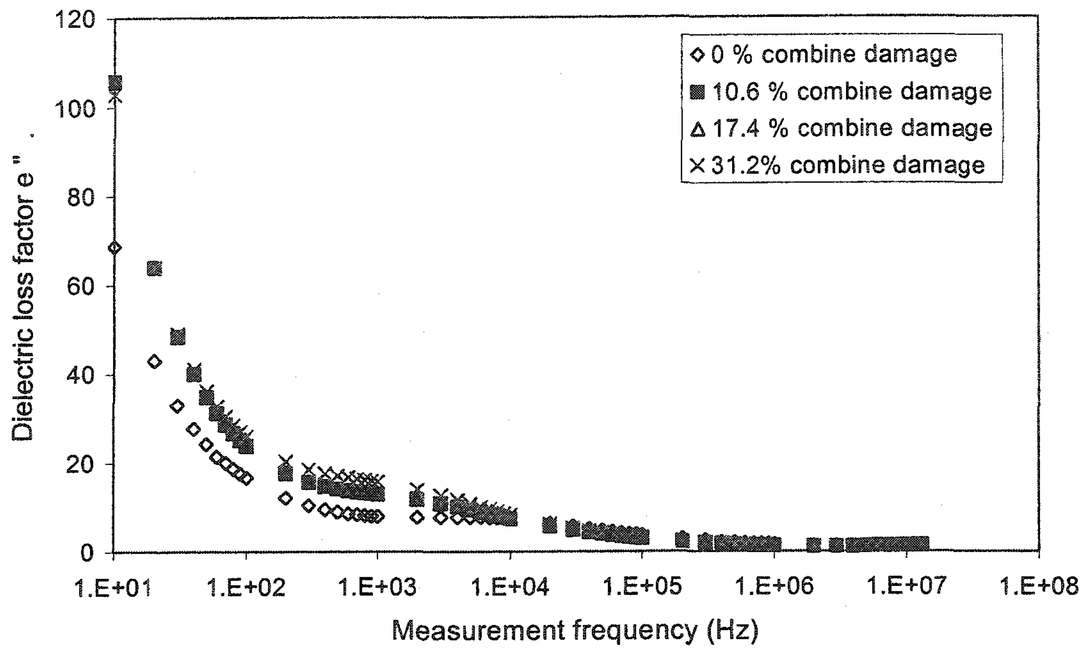

Figure 3.33. Dielectric loss factor for 18 % MC, uncompressed samples.

than other damage levels at frequencies above 1 kHz. The bulk density was apparently affecting the response, although, it did not appear to explain the differences between the dielectric constant values at 31.2 and 10.6 damage percent, where both damage levels had the same bulk density (0.716 g/cm^3) but different dielectric constant values. This difference was most probably due to the effect of mechanical damage since bulk density and moisture were the same. The dielectric loss factor response shown in figure 3.33 was similar to the dielectric constant, with more separation among the different damage levels at the lower measurement frequencies (below 1 kHz).

Next, the dielectric constant and loss factor at the high moisture content at 23 percent were inspected as shown in figure 3.34 and 3.35. The response suggested again that both

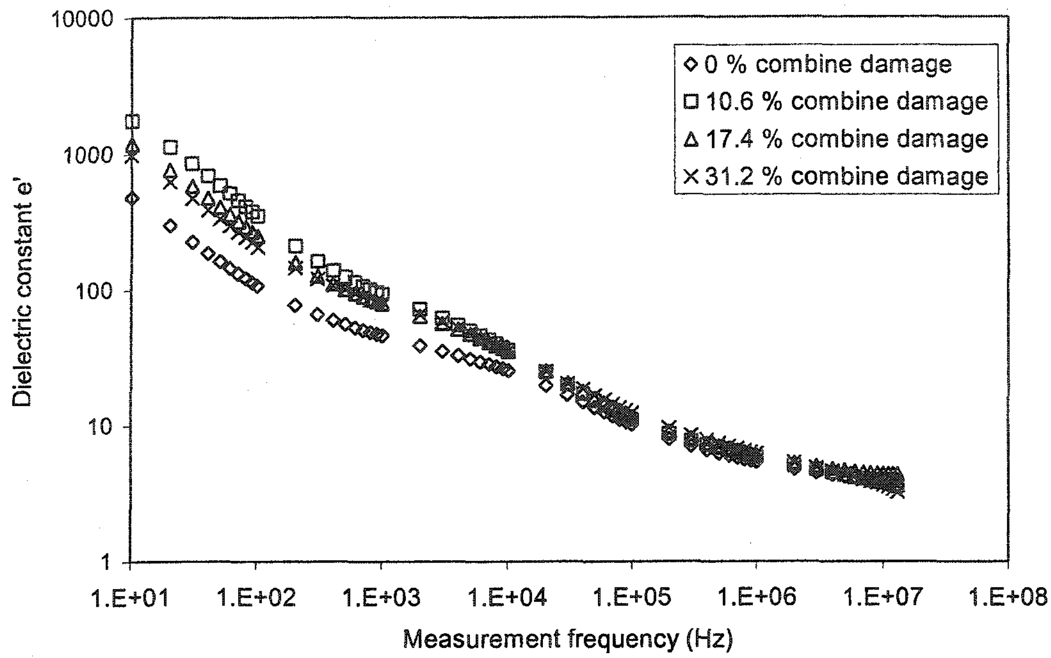

Figure 3.34. Dielectric constant for 23 % MC, uncompressed samples.

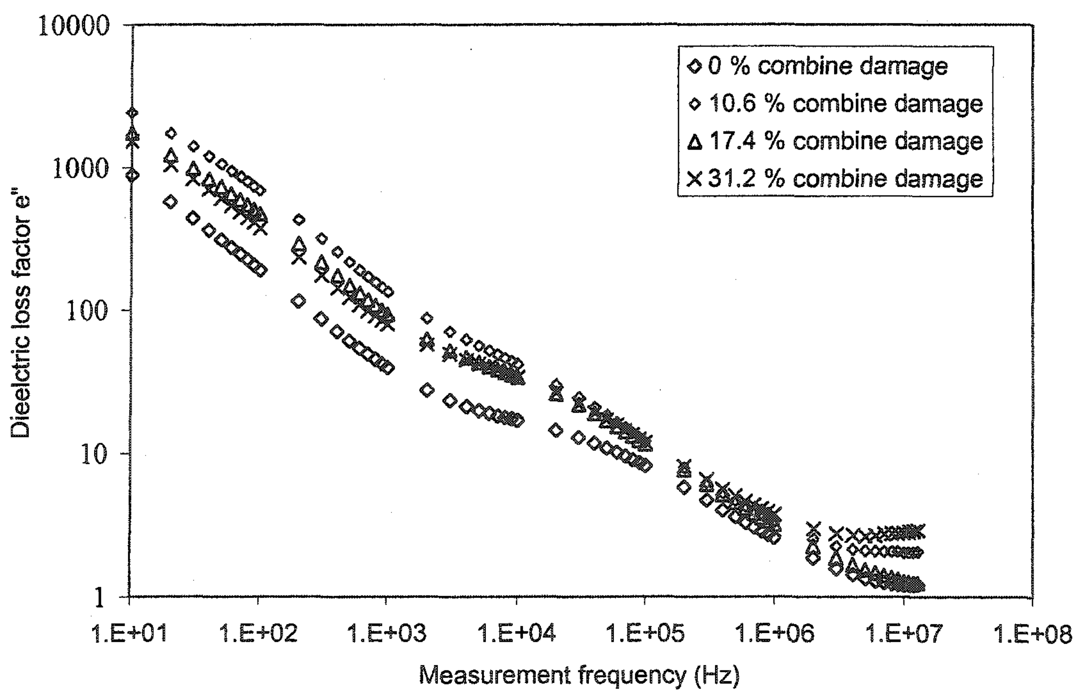

Figure 3.35. Dielectric loss factor for 23 % MC, uncompressed samples.

mechanical damage and bulk density affected the dielectric response to some extent. Finally, another set of similar plots was obtained for the compressed corn samples at the three moisture levels (not shown). Except for a shift in dielectric constant and loss factor values showing an increase in those values, the plots were very similar to uncompressed samples. The effect of moisture content on the dielectric response was clear. With increase in moisture content, both dielectric constant and loss factor increased. This increases was most significant at lower frequencies, which was due to the contribution of ionic conductivity term. This component, however, appeared to diminish as frequency increased since it is inversely proportional to frequency. Moreover, moisture content contributed to the dielectric response far more than bulk density or mechanical damage.

Statistical analysis

The plots of dielectric response for each of the three moisture content levels were discussed. The analysis provided a good understanding of the effect of the three variables (damage level, moisture content, and bulk density) on the dielectric response of the damaged corn samples. Analysis of variance (ANOVA) using SAS Proc Mixed (SAS 1999) was used to check for the significance of each variable used in the experiment as well as the significance of their interactions. The analysis of the experiment using this procedure was performed at every fifth frequency for the dielectric constant and loss factor similar to artificial damage, the results for the dielectric loss factor at a single frequency (600 Hz) is shown in table 3.10 as an example. The results showed that all the main factors and their interactions were highly significant at 1 % significance level. The blocks (replicates) were insignificant also, indicating low variations among the five replicates (low noise). The results

Table 3.10. Results of ANOVA for the combine damaged corn samples at ε''_{600Hz} .

Effect	Num Df	Den Df	F-Value	Pr > F
Block	4	8	1.33	0.3395
MC	2	8	150.19	0.0001
Damage%	3	36	17.95	0.0001
MC*damage%	6	36	16.15	0.0001
Compression	1	46	208.90	0.0001
Damage%*Compression	3	46	13.78	0.0001
MC*Compression	2	46	132.67	0.0001
MC*damage%*Compression	6	46	11.70	0.0001

also indicated that moisture content, compression level, and their interaction had a much larger effect on dielectric response than damage level. This suggested again that the effect of moisture content and bulk density represented a large proportion of the total dielectric response. The statistical significance of the least significance differences of means among damage levels was checked using the least square difference. The results for the dielectric loss factor at 600 Hz are shown in table 3.11. The table showed that all mean damage levels were significantly different from each other at 5 % significance level except for the 17.4 and 31.2 damage level pair. The results showed also that the difference between 10.6 and 17.4 percent damage level was highly significant, which did not agree with the earlier findings obtained from visual differences in the dielectric response plots. It should be pointed out, however, that these results represent a single frequency measurement, which may not necessarily account for all the parameters affecting dielectric response (moisture content, density, and mechanical damage)

Similar analysis was performed at the other measurement frequencies. The results showed that only low frequency measurements (below 100 kHz) were able to detect the

Table 3.11. Least significance difference of the means damage percent for combine damaged corn samples at ε''_{600Hz}.

Comparison pair		Statistical parameters		
Level 1	Level 2	Estimate[§]	t-value	Pr > |t|
0.0	10.6	-119.58	-7.15	<.0001
0.0	17.4	-44.42	-2.66	0.0117
0.0	31.2	-37.33	-2.21	0.0336
10.6	17.4	75.16	4.50	<.0001
10.6	31.2	82.24	4.87	<.0001
17.4	31.2	7.08	0.42	0.6775

[§]Standard error= 16.72

differences among the different damage levels while higher measurement frequencies were able to detect moisture content effect only. These findings suggested that lower frequency measurements demonstrated a better response to damage level variations than higher frequencies, which appeared to be consistent with the earlier findings. Dielectric loss factor showed a significant increase with frequency decrease, especially at the higher moisture contents. Therefore, any differences in damage level among the measured corn samples were amplified at the lower frequency measurements.

Mechanical damage prediction using dielectric properties

Corn samples were checked for spectral outliers. One observation was found to have negative dielectric properties. The observation was checked and graphed with samples at similar moisture content, bulk density, and mechanical damage level. The sample was significantly different from other similar samples and further investigation showed a measurement dip during sample measurement that caused this outlier. The outlier observation was then excluded from further analysis. Multiple Linear Regression, option maxr (SAS 1999) was used to screen the original variables. The model used mechanical damage evaluated using visual method as the response variable. The regression showed a weak correlation between dielectric parameters and mechanical damage percent ($R^2 = 0.36$) using a seven-variable model. A plot of the predicted versus actual mechanical damage percentage was checked for an explanation. It was observed that the predicted 10.6 percent damage observations were always underestimated by the regression model. Visual inspection of the dielectric response curves performed earlier indicated that the 10.6 percent damage level showed a response similar to the 17.4 percent damage level. This led to a conclusion that the two damage levels had some overlap and a wide variability among the actual damage level of the different replicates might have existed. Therefore, only one of the two damage levels was used in the regression model. Since the damage percent predictions associated with the 10.6 percent damage level samples were always underestimated by the regression model, those observations were deleted from the original data set and the regression was repeated using the other three damage levels only (0, 17.4, and 31.2 % damage) only.

Multiple Linear Regression using Maxr option was performed again on the new set of samples representing the three levels of mechanical damage. The coefficient of determination between damage percent and dielectric properties increased from 0.36 to 0.61 for the seven-variables model. Increasing the number of dielectric variables beyond seven variables did not show any significant increase in the coefficient of determination. A similar approach was used to correlate the damage percent level evaluated by Chowdhury's method as a response variable instead of visual inspection, with the dielectric properties of the corn samples. The result, however, were not different from the ones obtained when visual damage was used as the response variable.

The results showed that dielectric properties could explain up to 61 percent of the variation in mechanical damage percent using a seven-variable model, which might not be very useful for developing a model for damage level prediction. Earlier analysis performed on artificially damaged corn samples showed that addition of moisture content and bulk density to the dielectric variables improved the performance of the damage prediction model, therefore, the actual moisture content and bulk density were included in the regression model along with the dielectric variables and the variable selection technique using MLR option maxr was performed again. The results did not show any significant improvement, however, which suggested that the ability of the dielectric properties to predict mechanical damage level was masked by the effect of moisture content and bulk density. Since moisture content was the most predominant factor that affected the dielectric response of the corn samples, it was proposed that grouping the samples by moisture content would allow for picking up any dielectric effect remained as a result of mechanical damage. The corn samples were grouped into three classes according to their moisture content: low moisture class (12.5 %), medium moisture class (18 %) and high moisture class (23 %). It should be observed also that moisture content could be predicted using dielectric properties of the corn samples without a need for an external moisture measurement, which would essentially allow for predicting mechanical damage level using the dielectric properties alone. The variable selection procedure using MLR option maxr was used after classifying the samples by their moisture content. The results showed a significant improvement in regression model performance (table 3.12), which shows the coefficient of determination for the dielectric variables selected for each moisture content class using visual method as the damage evaluation method.

Table 3.12. Coefficient of determination for mechanical damage predicted using visual damage evaluation technique for each moisture class.

	Moisture content (W.B.)		
No. of variables	12.5 %	18 %	23%
2	0.77	0.74	0.91
3	0.83	0.75	0.94
4	0.87	0.87	0.97
5	0.90	0.90	0.98
6	0.95	0.95	0.98
7	0.97	0.96	0.99

It was observed from table 3.12 that 90 percent of the variability in damage percent was explained by using five dielectric variables in the regression model for low and medium moisture content (12.5 and 18 % respectively), while only two variables were able to explain approximately the same percentage in variability in damage percent for the high moisture samples (23 %).

Similar results were obtained when Chowdhury's method was used as the reference method for evaluating mechanical damage level (table 3.13). The results showed, however, that the overall performance of the damage prediction model using Chowdhury's method was slightly better for the five, six, and seven-variable models compared to the prediction model that used visual damage, using the same number of variables. Both damage evaluation methods, however, appeared to predict mechanical damage quite well. The results from table 3.12 and 3.13 are shown graphically on figure 3.36 and 3.37. The better prediction of mechanical damage percent at the high moisture class (23 %) compared to the other two moisture classes (18, and 12.5 %) was most probably due to the large contribution of moisture content to the overall dielectric response at the high moisture content.

Table 3.13. Coefficient of determination for mechanical damage predicted using Chowdhury damage evaluation technique for each moisture class.

	Moisture content (W.B.)		
No. of variables	12.5 %	18 %	23%
2	0.75	0.77	0.91
3	0.86	0.79	0.95
4	0.89	0.80	0.98
5	0.92	0.95	0.99
6	0.94	0.97	0.99
7	0.96	0.98	0.99

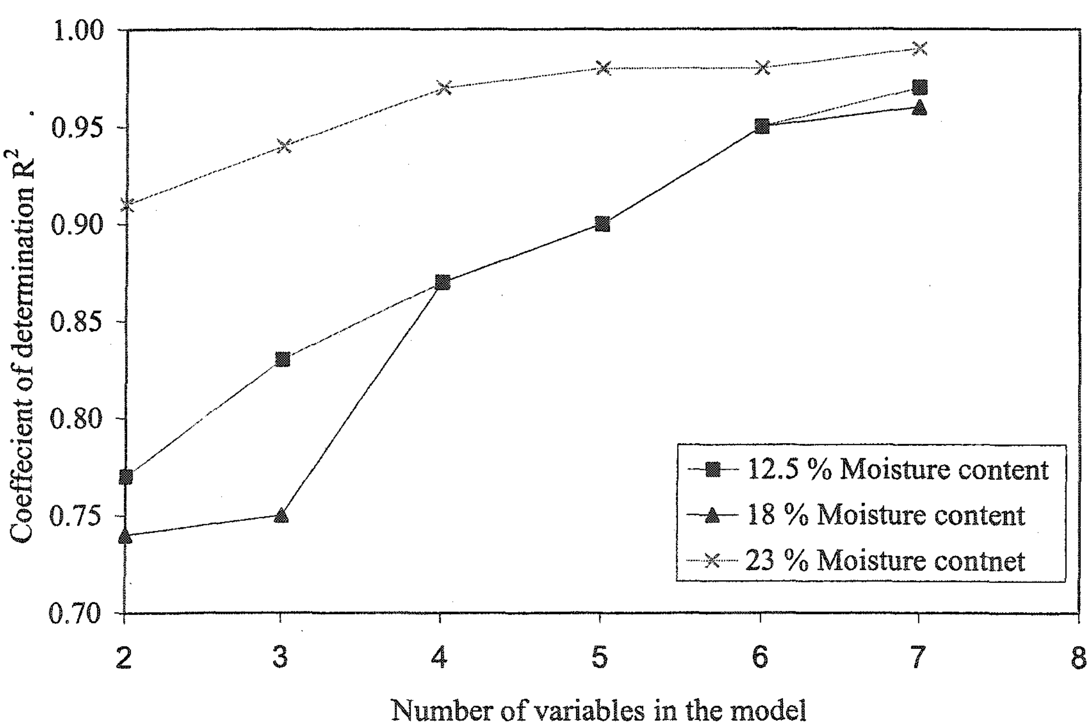

Figure 3.36. Coefficient of determination for mechanical damage predicted using visual damage evaluation technique for each moisture class.

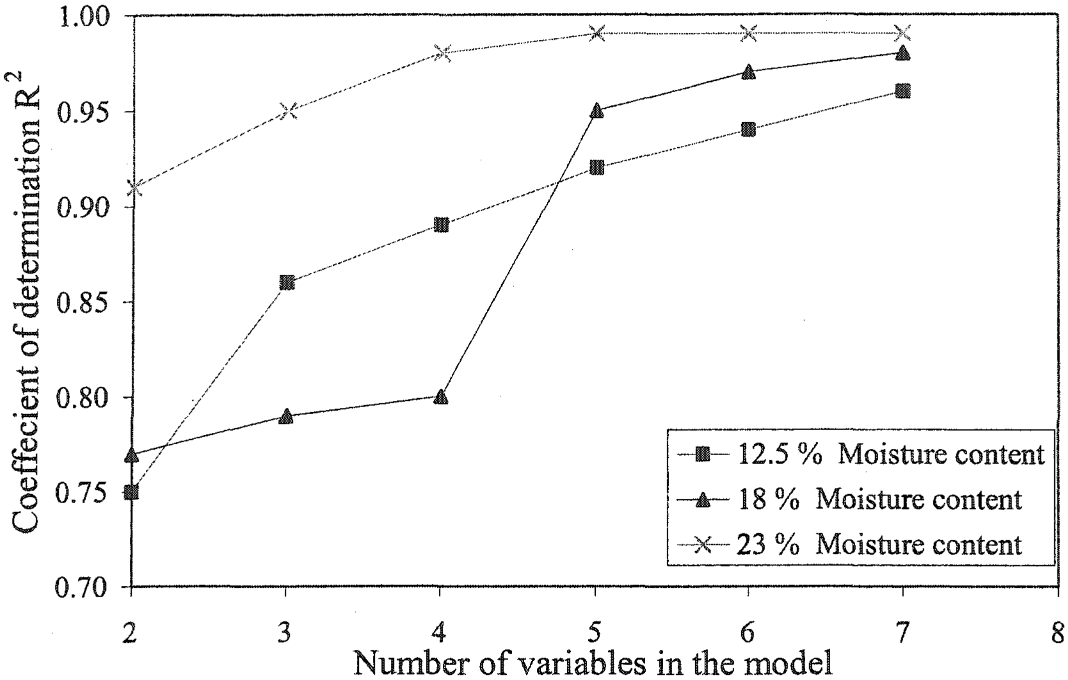

Figure 3.37. Coefficient of determination for mechanical damage predicted using Chowdhury damage evaluation technique for each moisture class.

Next, the variables selected using MLR method were used to develop a regression model for each moisture content class. General Linear Model (GLM SAS 1999) was used first to develop and refine the regression models then cross-validation was used to test the model ability to prevent overfitting by using cross validation. Partial Least Square Regression (PLS SAS 1999) was used to perform cross validation. The data were split into two parts, one part was used for calibration while the other was used for validation

Low moisture content (12.5 %)

The five-variable model was chosen and modified to include one higher order term. The addition of this term improved the coefficient of determination from 0.92 to 0.95 with a root mean square error (RMSE) of 3.36 %. The results are shown in table 3.14. All of the selected variables were significant at 2 % level. It was observed also that most of the frequencies

Table 3.14. Results of ANOVA for dielectric variables used in damage level prediction model for the low moisture class (12.5 %).

Parameter	Estimate	Std Error	t-value	Pr > |t|
Intercept	224.49	70.86	3.17	0.0046
$\varepsilon'_{20\ Hz}$	-2.66	0.71	-3.74	0.0012
$\varepsilon'_{30\ KHz}$	-289.08	49.09	-5.89	<.0001
Ln ($\varepsilon'_{0.3\ MHz}$)	1515.18	450.00	3.37	0.0029
$\varepsilon''_{50\ Hz}$	252.12	84.93	2.97	0.0073
Ln($\varepsilon''_{50\ Hz}$)	-1281.27	404.07	-3.17	0.0046
$\varepsilon''_{3\ KHz}$	403.33	54.62	7.38	<.0001
Ln($\varepsilon''_{50\ Hz}$)*Ln($\varepsilon''_{50\ Hz}$)	-12.53	5.01	-2.50	0.0208

selected by the model (20 Hz, 50 Hz, 3 kHz, and 30 kHz) were in the low frequency range which again supported earlier findings that dielectric measurements at lower frequencies were more successful in separating the different levels of corn mechanical damage.

Medium moisture content (18 %)

Parameter estimates for damage percentage regression model at medium moisture content (18 %) are shown in table 3.15. The five-parameter model, which included only three-frequency measurements, was used. The model had a coefficient of determination (R^2) = 0.95, and a root mean square error (RMSE) = 3.27. The frequencies picked up by the regression model were all in the low frequency side (10 Hz, 0.8 kHz, and 20 kHz), which also agreed with earlier findings.

High moisture content (23 %)

Parameter estimates for damage percentage regression model at high moisture content (23 %) are shown in table 3.16. The four-variable, three-frequency model developed by MLR are was used. The resulting ANOVA is shown in table 3.16. The model had a coefficient of determination (R^2) = 0.97, and a root mean square error (RMSE) = 2.29 percent. The frequencies picked up by the model were both at the low and high frequency sides. The 1Hz, and the 80 kHz were at the low side while the 0.4 MHz was at the high side.

Table 3.15. Results of ANOVA for dielectric variables used in damage level prediction model for the medium moisture class (18 %).

Parameter	Estimate	Std Error	t-value	Pr > |t|
Intercept	119.16	25.78	4.62	0.0001
$\varepsilon'_{10\ Hz}$	0.12	0.03	4.23	0.0003
$\varepsilon'_{20\ KHz}$	36.56	4.70	7.78	<.0001
$Ln\ (\varepsilon')_{10Hz}$	-165.71	27.51	-6.02	<.0001
$Ln\ (\varepsilon'')_{0.8\ kHz}$	310.14	29.29	10.59	<.0001
$Ln\ (\varepsilon'')_{20\ KHz}$	-663.22	67.76	-9.79	<.0001

Table 3.16. Results of ANOVA for dielectric variables used in damage level prediction model for the high moisture class (23 %).

Parameter	Estimate	Std. Error	t-value	Pr > |t|
Intercept	154.97	38.08	4.07	0.0004
$(\varepsilon')_{80\ KHz}$	-22.05	1.76	-12.56	<.0001
$(\varepsilon')_{0.4\ MHz}$	95.11	6.78	14.02	<.0001
$Ln(\varepsilon')_{1kHz}$	-842.28	103.91	-8.11	<.0001
$Ln(\varepsilon'')_{0.4\ MHz}$	133.60	19.58	6.82	<.0001

Plots of predicted versus observed mechanical damage for each of the three moisture content classes are shown in figure 3.38 through 3.40.

Next, partial least square regression was used to test for overfitting using the prediction sum of squares (PRESS), which was calculated based on cross validation algorithms utilized by Partial Least Square method. PRESS is defined as:

$$PRESS = \sum_{i=1}^{n} (Y_i - \hat{Y}_{i(j)})^2 \qquad (3.17)$$

where:

Y_i : is the measured damage percentage using visual inspection or Chowdhury test.

$\hat{Y}_{i(j)}$: is the predicted damage values (j) using the calibration model developed using the (i-j) percentage damage observations, and n is the total number of observations used in both calibration and prediction.

Smaller values of PRESS indicate a better model prediction ability. Proc PLS, (SAS 1999) was used with split option for cross validation, where, every seventh observation was

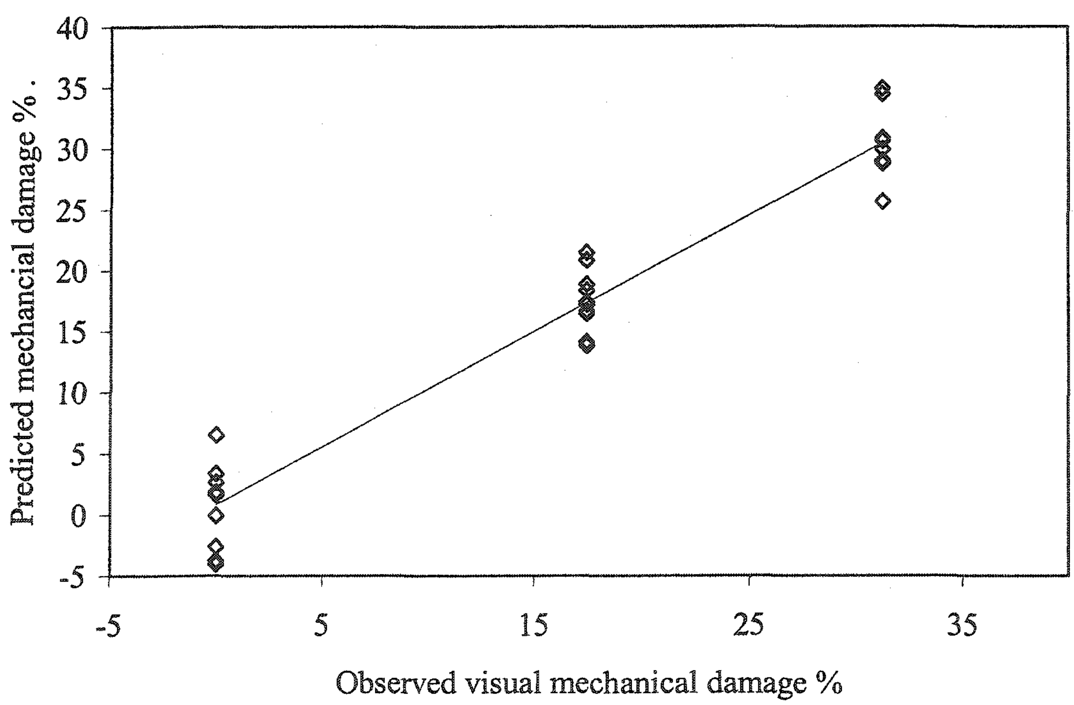

Figure 3.38. Predicted versus observed visual mechanical damage for the low moisture corn samples (12.5 %).

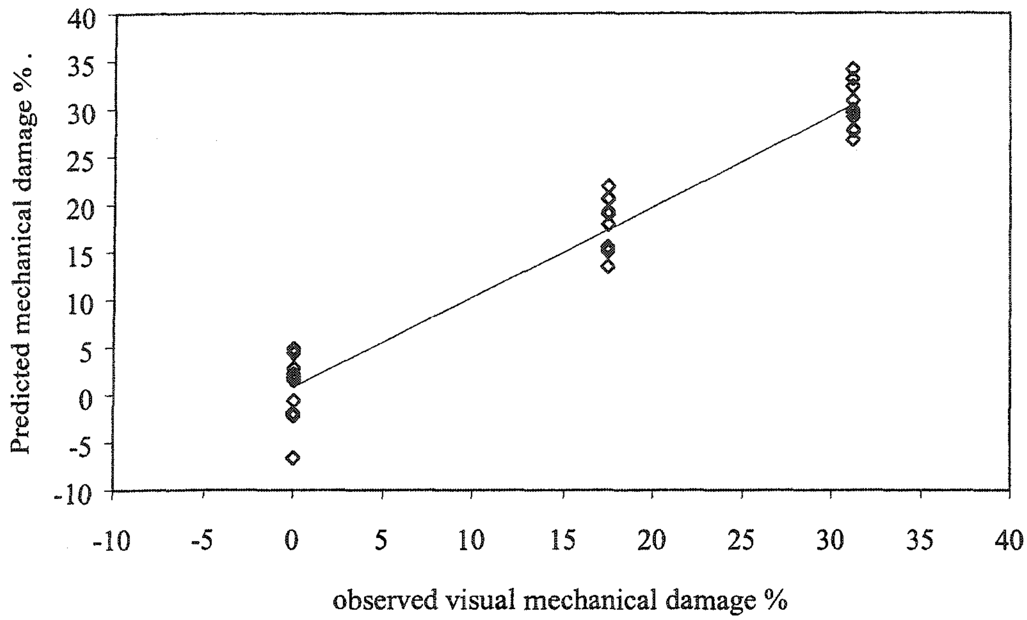

Figure 3.39. Predicted versus observed visual mechanical damage for the medium moisture samples at (18 %).

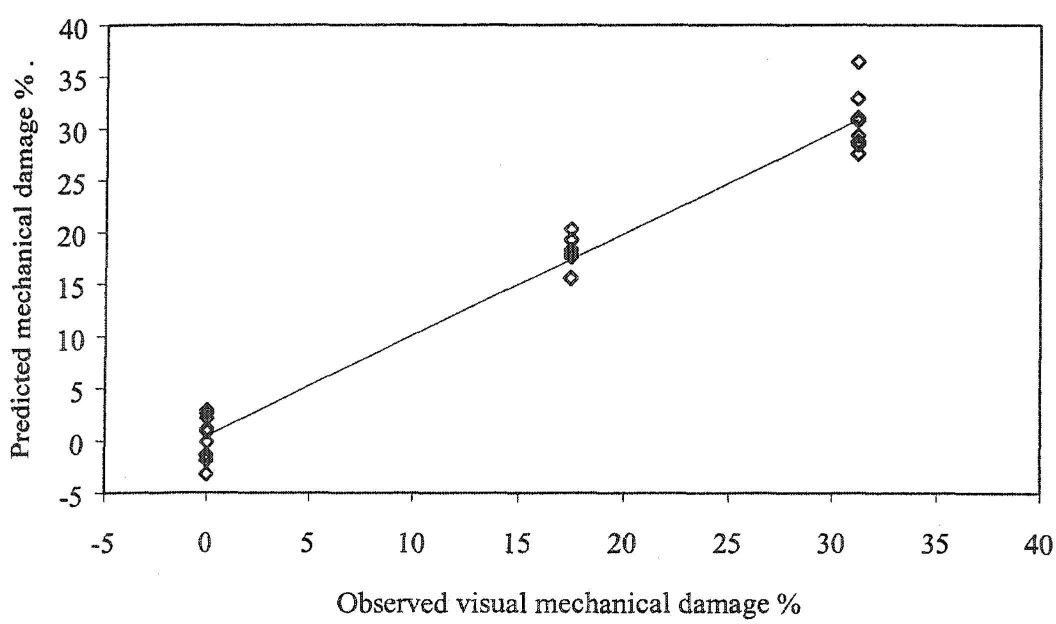

Figure 3.40. Predicted versus observed visual mechanical damage for the high moisture samples at (23 %).

excluded from calibration and used for prediction. For damage prediction at the low moisture content (12.5 %), PRESS value was 0.309, which is fairly low indicating a good prediction ability of the model developed by calibration. The damage prediction model was obtained also using PLS. The model was similar to the one obtained earlier from GLM procedure indicating no overfitting problems. For medium moisture content (18 %), PRESS value was 0.34 which was slightly higher than the PRESS value associated with the low moisture model. PLS was also used to develop a calibration model for damage at this moisture class. The results were similar to the ones obtained using MLR, indicating no overfitting problem. For high moisture content (23%), PRESS value was 0.25, which was the lowest among the three moisture levels, RMSE, was also the lowest among the three moisture levels. No overfitting problem was observed with this moisture level also.

The results showed that mechanical damage could be predicted using dielectric properties. The main limitation of this approach was that samples were classified into three moisture content classes, and a separate calibration was needed for each moisture class. Moisture content, however, could be easily predicted using dielectric properties, therefore, a sensor could be developed for predicting damage using dielectric properties alone. The need for a separate damage prediction model for each moisture class might be eliminated if moisture classes were more closely spaced, which could result in a single model that could be used for predicting mechanical damage percent regardless of the sample moisture content. Next, regression models for moisture content and bulk density were developed.

Moisture content and bulk density prediction

A model was developed for predicting moisture content using two of the variables used previously for developing the regression model for damage level, which in essence did not increase the overall number of dielectric variables beyond the ones that were used for predicting damage level. The following model was obtained:

$$MC = 0.0932 + 0.946\text{Log}\,(\varepsilon')_{0.3MHz} - 0.924\text{Log}\,(\varepsilon')_{1MHz} \qquad (3.18)$$

Predicted values obtained using this model versus the actual moisture content obtained using the standard oven method are shown in figure 3.41. The model had an $R^2 = 0.98$ and, RMSE = 0.57 %. Moisture content prediction was not very sensitive to the frequency used. Using a single frequency model resulted in an $R^2 = 0.90$ approximately, and adding another frequency to the model increased R^2 from 0.90 to about 0.98. Since moisture content was predicted quite well using two of the dielectric variables used in damage level prediction, it

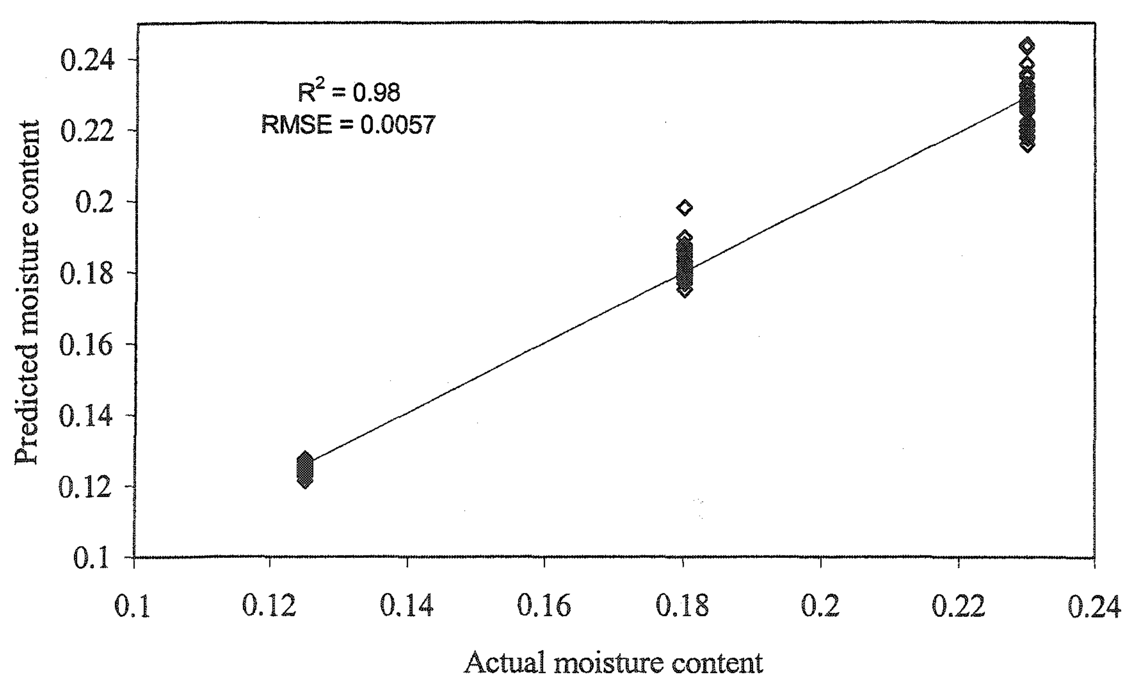

Figure 3.41. Moisture content prediction using two dielectric variables model.

was concluded that only the dielectric variables used to predict damage level were needed. Therefore, damage level prediction will involve two steps, in the first step, moisture content will be predicted, then in the second step the appropriate damage prediction model will be selected based on that moisture content. not needed for damage prediction, it was listed here to point out the ability of dielectric variables to predict it without the need for using additional variables. A plot of the A similar prediction model was developed for bulk density using four of the dielectric variables that were used for predicting damage level. Although, determining bulk density was results is shown in figure 3.42 and the parameter estimates for predicting bulk density are shown in table 3.17. The regression model had an $R^2 = 0.96$ and a RMSE = 0.011 g/cm^3.

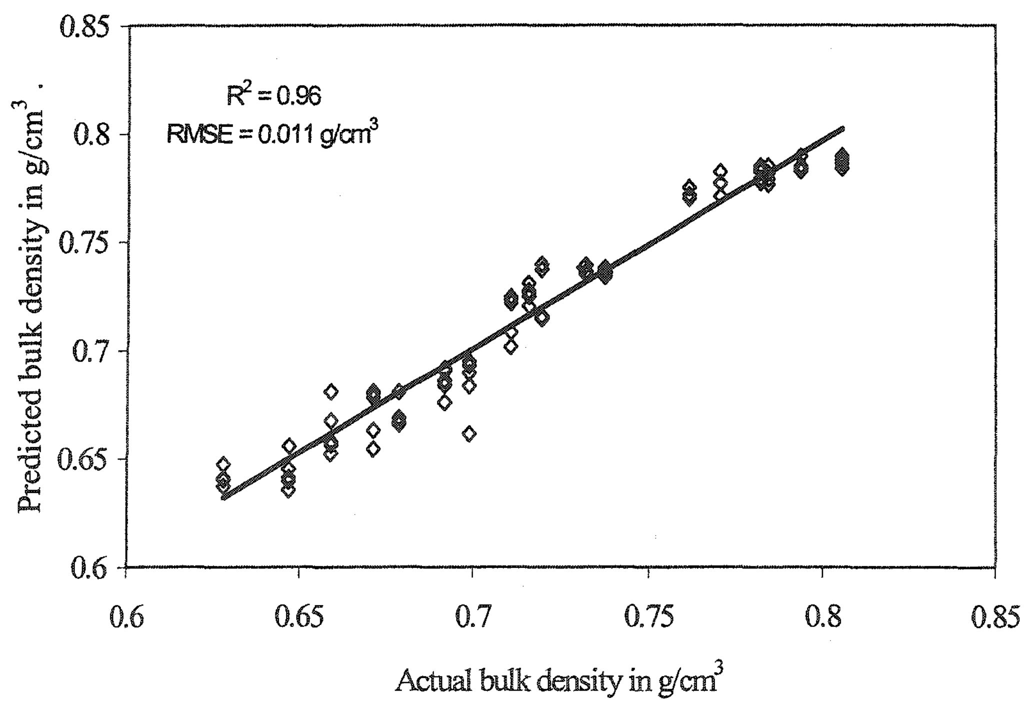

Figure 3.42. Actual versus predicted bulk density using the four-variable regression model.

Table 3.17. Results of ANOVA for bulk density prediction model.

Parameter	Estimate	Std Error	t-value	Pr > |t|
Intercept	0.36	0.04	8.76	0.0001
Log $(\varepsilon'')_{80Hz}$	-0.24	0.02	-11.59	0.0001
Log $(\varepsilon'')_{300Hz}$	0.54	0.03	17.08	0.0001
Log $(\varepsilon'')_{20KHz}$	-0.47	0.02	-21.00	0.0001
Log $(\varepsilon')_{1MHz}$	0.64	0.07	8.65	0.0001

Conclusions

The research conducted in this project indicated that dielectric properties have a good potential for developing a corn mechanical damage sensor. The project investigated artificially damaged and combine damaged corn samples and showed that both types of mechanical damage could be detected using dielectric properties of corn. The major findings of this research projects are:

1. For artificially damaged corn samples, dielectric properties of severe and medium damaged corn were successfully used to develop a damage level prediction sensor. The prediction accuracy of medium damaged corn samples was improved by introducing the actual moisture content and bulk density to the dielectric variables. When predicted moisture content and bulk density were used, however, the model performance deteriorated substantially.
2. For combine damaged corn samples, dielectric properties of severe and medium damaged corn were also used successfully to develop a damage level prediction sensor. The prediction, however, was developed for each moisture class separately.

3. The results obtained from both artificial and combine mechanical damage indicated that dielectric measurements at frequencies below 100 kHz had a good potential for developing a mechanical damage sensor. However, more corn samples and more varieties might be needed to develop such sensor.
4. It was found that the effect of moisture content and bulk density on the dielectric response of the corn samples was much larger than the effect of mechanical damage and a proper compensation for those two parameters was essential before making any successful attempts to measure mechanical damage. This was observed for both artificial and combine damage.
5. Dielectric variables provided a good prediction of moisture content and bulk density regardless of damage type or severity.
6. The study suggested that dielectric variables have the potential to be used to develop a fast and practical mechanical damage sensor.

Recommendations for further study

Further research is needed to apply this method for more corn samples, corn varieties, corn types, bulk densities, temperature, and moisture contents. The method should be also investigated for other grain types such as soybeans and wheat.

In order to establish more control over the combine mechanical damage levels; these damage levels could be prepared by mixing weight proportions of combine damaged and undamaged corn. This method will help reducing the variation within damage level itself (between one replicate and another).

A wider range of measurement frequencies and a DC measurement could be helpful in improving damage measurements. Frequencies below 100 kHz appeared to be most useful. However, higher frequency measurements might improve mechanical damage prediction and reduce the number of variables used in the model. A wider frequency range will help avoiding the use of collinear variables also.

The dielectric measurements have other potential applications beside measuring mechanical damage. They could be used to measure corn deterioration especially in the audio and radio–frequency range (below 100 kHz). Other applications include the possibility of developing non-destructive quality measurement methodology, and the development of grain flow sensors.

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APPENDIXIES

Appendix I : RF and MW drying and heating.

A brief discussion of the dielectric heating and drying theory is discussed next. In heating or drying dielectric materials, the power dissipated per unit volume is given as

$$P = E^2\sigma = 55.63x10^{-12} fE^2\varepsilon'' \tag{1}$$

where E is the rms of electric field intensity in (V/m). The time rate of temperature increase caused by conversion of electric field energy into heat in (^{0}C/s) is:

$$\frac{dT}{dt} = \frac{P}{C_p.\rho} \tag{2}$$

where: C_p is the specific heat of the material in kJ/kg.^{0}C and ρ is the density in kg/m^3. The penetration depth, which is by definition the distance at which the power decays to 1/e=1/2.7183 of its value at the surface of the material (Risman, 1991) is given by the expression:

$$dp = \frac{\lambda_o}{2.\pi.(2\varepsilon')^{1/2}}\left[(1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2)^{-1/2} - 1\right]^{-1/2} \tag{3}$$

where λo is the free-space wavelength of the electric field. Part of a plane wave incident upon a material will be reflected and the other part will be transmitted through the material. This is given by the following relationship:

$$P_t = P_0\,(1-|\Gamma|^2) \tag{4}$$

Where P_t is transmitted power, P_0 is total power and Γ is the reflection coefficient which be expressed as:

$$\Gamma = \frac{1-\sqrt{\varepsilon}}{1+\sqrt{\varepsilon}} \tag{5}$$

where ε is the complex relative permittivity of the material (Nelson, 1991).

The power density decays as an exponential function of the attenuation (α) and the distance traveled (Z) as the wave propagates through the material. This is expressed by the following relationship

$$P = P_t e^{(-2 \alpha Z)} \tag{6}$$

where P is the power at a distance z from the material surface.

Appendix II: USDA definition of grain damage.

DAMAGED KERNELS

The most common types of kernel damage are germ-, frost-, immature-, heat-, mold-, scab-, sprout-, insect-, ground-, and cob rot-damage. Most of these types of damage result in some sort of discoloration or change in kernel texture.

Determine the percent of damaged kernels in the sample by hand-picking a dockage-, foreign material-, and/or shrunken and broken-free portion. To determine whether an individual kernel is damaged, examine the entire surface of the kernel.

Interpretive line slides have been developed to help inspectors with this determination. These are photographic slides of actual kernels. Each slide shows the minimum amount of discoloration or deterioration necessary for a kernel to be considered damaged. In addition, several land-grant universities have prepared brochures that provide color photographs depicting the various types of kernel damage.

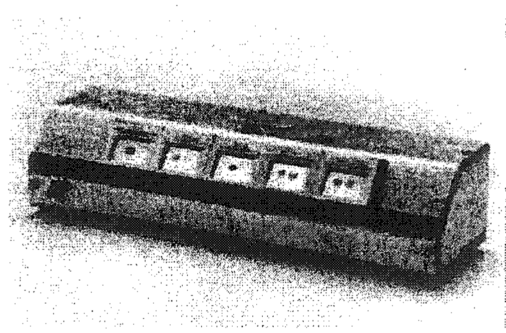

Figure 9. Interpretive Line Slides and Viewer.
(Courtesy: Seedburo Equipment Co., Chicago, Illinois)

Type of Damage	Grain	Characteristics
Bee's Wings-Damaged Kernels	Corn and Flaxseed	Kernels that are very thin, whitish, and paperlike.
Black Tip Fungus-Damaged Kernels	Wheat	Kernels with black tip fungus growth on the germ and in the crease of the kernel.
Blue-Eye Mold-Damaged Kernels	Corn	Kernels with blue mold in the germ. Blue-eye mold should not be confused with purple plumule, which is not a type of damage. Purple plumule is generally purple in color and is always found in the center of the germ.
Cob Rot-Damaged Kernels	Corn	Kernels that are distinctly discolored or rotting as a result of a fungus that attacks corn ears.
Drier-Damaged Kernels	All Grains	Kernels that are discolored, wrinkled, and blistered; or are puffed or swollen and slightly discolored, and often have damaged germs; or whose seed coats are peeling off or appear fractured.

Type of Damage	Grain	Characteristics
Frost-Damaged Kernels	All Grains	Kernels that are discolored, blistered, or have a slightly flaked-off bran coat; or kernels with a distinctly wax-like or candied appearance due to frost.
Germ-Damaged Kernels	All Grains	Kernels that are discolored by heat or mold resulting from respiration.
Ground- or Weather-Damaged Kernels	All Grains	Kernels with dark stains or discolorations and rough cake-like appearance caused by ground and/or weather conditions.
Heat-Damaged Kernels	All Grains	Kernels that are materially discolored and damaged by external heat or as the result of heating caused by fermentation.
Immature- or Green-Damaged Kernels	All Grains	Kernels that are intensely green in color.
Malt-Damaged Kernels	Barley	Kernels that have undergone the malting process and show any degree of sprout.
Mold-Damaged Kernels (External)	All Grains	Kernels that have <u>considerable</u> evidence of mold.

Type of Damage	Grain	Characteristics
Mold-Damaged Kernels (Internal)	All Grains	Kernels that have <u>any</u> evidence of mold.
Purple Pigment-Damaged Kernels	Sorghum	Kernels materially discolored by purple pigment.
Scab-Damaged Kernels	Wheat	Kernels having a dull, lifeless, and chalky appearance.
Sprout-Damaged Kernels	All Grains	Kernels that are sprouted.
Stinkbug Stung-Damaged Kernels	Soybeans	Kernels that, in cross-section, show damage caused by stinkbugs. Score stinkbug stung-damaged kernels at the rate of one-fourth of the actual percentage.
Weevil- or Insect-Damaged Kernels [1/]	All Grains	Kernels which bear evidence of boring or tunneling by insects.

1/ If two or more insect-damaged kernels are found in a 15-gram portion of wheat, examine a second 15-gram portion. If two or more insect- damaged kernels are found in the second portion, examine a 70-gram portion and then combine the number of insect-damaged kernels found in all three portions. If 32 or more insect-damaged kernels are found in the combined portions (i.e., 100 grams) grade the wheat "U.S. Sample grade." If fewer than two insect-damaged kernels are found in either the first or second portion, discontinue the examination.

Appendix III: SAS tutorial

A. Using SAS

Importing a data file:

File > import file > Specify the format of the file (i.g. Microsoft Excel 97 or 2000 (*xls) >Next > Browse > the open file menu opens up, then choose the input data file and click open > the menu returns to SAS wizard, from SAS wizard push option button to choose the specific spreadsheet within the input file> a new menu appears from the scroll down menu, choose the spreadsheet > click ok > next > in the right hand window type the name of the file (i.g. **damage**).> next> click finish> wait until a message in the *log window* appears saying work.file successfully created (i.g. **work.damage**).

If this message appears, then the input file is successfully created and you can start working on the data.

B. Used procedures

PROC MEANS:

A simple program for calculating the means of the variables:

Type the following code in the *Editor window:*

```
proc contents data=Work.damage; run;
proc means; run;
```

The first line specifies the input file as **work.damage**, the second line uses the procedure **MEANS** to calculate some simple statistics, and the run statement executes the program.

The following programs were used throughout the research:

PROC REG

This program uses optimization methods to select a specific number of variables that explain most of the variation in the response variables: (all comments (*in italics)* start with /* and end with */)

```
proc contents data=Work.damage; run;

/* the following statement sorts the observations by mc, however,
the level of
moisture contents should be first sorted in the excel spread sheet
*/

proc sort; by mc;run;

/* Proc reg performs variable selection, the dependent variable is
the left
hand side variable in the model  statement and the range of the
variables is specified b1-b58 g3-g58 */

proc reg data=Work.damage;
by mc;
  model damagepercent=b1-b58 g3-g58/

/*the method specifies the optimization option like stepwise, maxr,
forward, etc
  The other options include cp statistic, VIF: variance inflation
factor,
  adjresq: adjusted R^2, sbc is a test statistic mse: mean square
error, best option gives the best two models (stepwise option)
   stop: gives the number of variables to include in the model (maxr
option)
   Sle: is the selection Alpha (stepwise option)*/

Method = maxr cp vif aic adjrsq sbc mse best=2 stop=3 sle=.05;

/* output file for the results output, predicted values, residual
values
       and standard error of residuals */

output out=new p=pred r=resid stdr=eresid;
run;

/*plotting the results
Vpercent and VTOH: the dimensions of the graph
```

```
Plot pred*damagepercent plots the predicted damage against the
actual damage
and plot resid*damagepercent plots the damage residuals against the
damage */

proc plot VPERCENT=75 VTOH=10;
 plot pred*damagepercent;
 plot resid*damagepercent;
 run;
```

PROC GLM

Proc GLM (General Linear Model) is used to obtain the regression model, the analysis of variance for the variables selected in MLR step, the Coefficient of determination (R^2) and Root Mean Square Error (RMSE).

The following is a sample code program:

```
proc contents data=Work.damage; run;

/*proc sort sorts the samples by their mc level */

proc sort; by mc ; run;

/*proc GLM is excuted on the data file work.damage*/

proc GLM data=Work.damage;

/*the analysis is categorized by the moisture content*/

by mc;

/*
the |@2 gives all the 2-way interactions of the variables used
the other options include type os ss (ss1 or ss2) and predicted
which lists the predicted values of damage percent (the response
variable) as a function of the predictor variables
*/

  model  damagepercent=b42|g49|g100|density @2/ss3 predicted;

/* the output file and its options */

 output out=new p=pred r=resid stdr=eresid;  run;
```

PROC MIXED

Proc Mixed is used to obtain the ANOVA of model that has a combination of random and fixed variables. Least Significant Difference (LSD) allows also for testing the least significant difference among the different treatments.

The following program code was used:

```
proc contents data=Work.damage; run;
  proc mixed data=Work.damage;

/* class statement specifies the variables as classes */

  class block MC damagepercent compression;

/*
the model uses one dielectric measurement at a time to
run the proc mixed statement the variables on the right
hand side of the model statement are the fixed variables
and interactions ( a fixed variable is the one that takes a definite
number of values while a random variable has an indefinite number of
values
*/

  model g5=
  block MC damagepercent
  MC*damagepercent
  compression compression*damagepercent compression*MC
  compression*damagepercent*MC;

/* the random statement is used for the random variables */

  random block*MC
         block*damagepercent*MC;

/* least significant means test amdong the damagepercent values*/

  lsmeans damagepercent/adjust=bon;
run;
/* linear combination of the damagepercent levels
 0, 10, 25, 50, and 100*/

contrast' linear damagepercent'
          damagepercent -37 -27 -12 13 63;
            run;
```

PROC PLS

Proc PLS uses partial least square regression to obtain the regression model, the procedure can uses PLS option, PCR (principle component regression) and RRR(reduced rank regression to develop the regression method, it has a cross validation option to test the validity of the model for future prediction.

The following program code was used:

```
proc contents data=Work.damage; run;
proc sort; by mc ; run;

/*
Method option specifies the regression technique (PLS,PCR,RRR)
Cvtest option automatically drop the factors that are statistically
insignificant
Cv=option (specifies the cross validation option: one, block,
split, Random)
Anova option: gives soem regression model details.
Details option: gives the details of the model including scores and
loading
*/
proc pls data=Work.damage  method=pls cvtest cv=split anova
details;
by mc;

/*
solution option gives the regression coefficient (centered and
scaled and raw coefficients)
*/

model damagepercent=b35 b40 b104 g98/solution;

/* pdamagepercent predicts damagepercent as an output file */

output out=pred pdamagepercent ;
run;
proc print data=pred;

/* prints out the predicted damagepercent on the screen */

var pdamagepercent;
```

Appendix IV : Quick BASIC Control code.

```
DECLARE FUNCTION SciCon$ (dum)
DECLARE SUB conversion (intg, dec, dumvalue)
COMMON startf, stopf, stepf, sweepend, sampleid
DECLARE SUB Instructions ()
DECLARE FUNCTION InitMeter% (DevName$)
DECLARE SUB ReadIDString (device%)
DECLARE SUB TakeMeasurement (device%)
DECLARE SUB WriteCommand (device%, Cmd$)
DECLARE FUNCTION ReadValue% (device%, BUFFER$, buflen%)
DECLARE SUB PrintErrors (ErrStr$)


'$INCLUDE: 'DECL.BAS'
'************************************************************************
'
' File:   SAMPLE.BAS
'
' Sample program for GPIB Quick BASIC library
'
'
' This is a program that sets the LF 4192A impedance analyzer
' and then prints voltage measurements to the screen
'
'************************************************************************

CONST DEV = "Imp-ana"
CONST RESETCMD = "*RST"
CONST IDCMD = "*IDN?"
CONST MEASURECMD = "VAL?"

CONST BUFSIZE = 256           ' Size of IBRD buffer
CONST NULLCHAR = 2            ' Character to fill IBRD buffer with

CONST FALSE = 0
CONST TRUE = 1

'************************************************************************
**
'
' Name:        Global Variables Definition
'
'*********************************************************************

' Status bits (in ibsta%) and their names
   DIM SHARED StatBits(20):
   DIM SHARED StatBits$(20)
   StatBits(0) = DCAS:   StatBits$(0) = "DCAS"
   StatBits(1) = DTAS:   StatBits$(1) = "DTAS"
   StatBits(2) = LACS:   StatBits$(2) = "LACS"
   StatBits(3) = TACS:   StatBits$(3) = "TACS"
   StatBits(4) = AATN:   StatBits$(4) = "AATN"
   StatBits(5) = CIC:    StatBits$(5) = "CIC"
```

```
   StatBits(6) = RREM:   StatBits$(6) = "RREM"
   StatBits(7) = LOK:    StatBits$(7) = "LOK"
   StatBits(8) = CMPL:   StatBits$(8) = "CMPL"
   StatBits(9) = eevent:  StatBits$(9) = "EVENT"
   StatBits(10) = SPOLL: StatBits$(10) = "SPOLL"
   StatBits(11) = RQS:   StatBits$(11) = "RQS"
   StatBits(12) = SRQI:  StatBits$(12) = "SRQI"
   StatBits(13) = EEND:  StatBits$(13) = "EEND"
   StatBits(14) = TIMO:  StatBits$(14) = "TIMO"
   StatBits(15) = EERR:  StatBits$(15) = "EERR"
   StatBits(16) = 0:     StatBits$(16) = ""

' Error bits (in iberr%) and their names
   DIM SHARED ErrCodes(20):
   DIM SHARED ErrCodes$(20)
   ErrCodes(0) = EDVR:   ErrCodes$(0) = "EDVR"
   ErrCodes(1) = ECIC:   ErrCodes$(1) = "ECIC"
   ErrCodes(2) = ENOL:   ErrCodes$(2) = "ENOL"
   ErrCodes(3) = EADR:   ErrCodes$(3) = "EADR"
   ErrCodes(4) = EARG:   ErrCodes$(4) = "EARG"
   ErrCodes(5) = ESAC:   ErrCodes$(5) = "ESAC"
   ErrCodes(6) = EABO:   ErrCodes$(6) = "EABO"
   ErrCodes(7) = ENEB:   ErrCodes$(7) = "ENEB"
   ErrCodes(8) = EOIP:   ErrCodes$(8) = "EOIP"
   ErrCodes(9) = ECAP:   ErrCodes$(9) = "ECAP"
   ErrCodes(10) = EFSO:  ErrCodes$(10) = "EFSO"
   ErrCodes(11) = EBUS:  ErrCodes$(11) = "EBUS"
   ErrCodes(12) = ESTB:  ErrCodes$(12) = "ESTB"
   ErrCodes(13) = ESRQ:  ErrCodes$(13) = "ESRQ"
   ErrCodes(14) = ECFG:  ErrCodes$(14) = "ETAB"
   ErrCodes(15) = ETAB:  ErrCodes$(15) = "ECFG"

   ErrCodes(16) = 0:     ErrCodes$(16) = ""

' GPIB Read buffer
   DIM SHARED BUFFER$(BUFSIZE)


'***************************************************************************
**
'
' Name:         Main Program
'
' This programs prints instructions on the screen, opens and
' initializes the LF 4192A Impedance analyzer, Reads and prints the  '
'  analyzer ID string.
'
'***************************************************************************
**

CLS
LOCATE 8, 15: COLOR 10
PRINT
"***********************************************************************"
```

```
PRINT "                    This program is written by:
"
PRINT "  Majdi Al-Mahasneh, Dr. Stuart Birrell        "
PRINT
"**********************************************************************"
SLEEP 4
CLS
    LOCATE 1, 1: COLOR 15
    INPUT "File_name ", filename$
    OPEN   filename$ FOR OUTPUT AS #2

2 CLS
LOCATE 1, 1: COLOR 10
PRINT " Enter measurement choice as follows :                              "
PRINT " s. For short circuit measurement                                   "
PRINT " o. For open circuit measurement                                    "
PRINT " m. For Sample  measurement                                         "
PRINT " e. To exit the programe                                            "
INPUT " Enter your choice s, o, m or e : ", t$
IF t$ = "s" THEN
TT$ = "Short"
PRINT
"**********************************************************************"
PRINT ""
PRINT "   ...  Please Prepare the short circuit measurement .... "
PRINT ""
PRINT
"********************************************************************"
SLEEP 3
GOTO 75
ELSEIF t$ = "o" THEN
TT$ = "Open"
PRINT
"**********************************************************************"
PRINT ""
PRINT "  …Please Prepare the Open-circuit measurement.........     "
PRINT ""
PRINT
"********************************************************************"
SLEEP 3
GOTO 95
ELSEIF t$ = "m" THEN
TT$ = "Sample"
PRINT
"**********************************************************************"
PRINT ""
PRINT "   ...  Please Prepare the sample measurement.............     "
PRINT ""
PRINT
"********************************************************************"
SLEEP 3
GOTO 85
ELSEIF t$ = "e" THEN
PRINT " you are leaving ... good by"
GOTO 105
```

```
ELSE
PRINT "sorry invalid choice......."
GOTO 2
END IF
' open  sample measurement cycles,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,
85

'*******************************************************************
  LOCATE 9, 1: COLOR 15
  PRINT #2, DATE$, TIME$
  PRINT #2, filename$
  PRINT #2, "sampleid", "RH", "Temp", "Mode", "sweep",
            u = .01
12      FOR i = 1 TO 9
            F = u * i
            IF F <= 10000 THEN
            PRINT #2, "G" + LTRIM$(STR$(F)), "B" + LTRIM$(STR$(F)),
            ELSE GOTO 13
            END IF
       NEXT i
            u = F + F / 9
            GOTO 12
13      FOR j = 11 TO 13
            F = j * 1000
            PRINT #2, "G" + LTRIM$(STR$(F)), "B" + LTRIM$(STR$(F)),
        NEXT j

        PRINT #2, "END_OF_LINE"

102 INPUT " Enter sample_ID", sampleid$
    LOCATE 23, 1: COLOR 10
    INPUT "Are you sure this is the correct sample ? Y/N", C$
    LOCATE 23, 1
    PRINT "                                                          "
                IF C$ = "n" THEN C$ = "N"
                IF C$ = "y" THEN C$ = "Y"
                    IF C$ = "Y" THEN
                    GOTO 15
               ELSE
                GOTO 102
    END IF
15
20  CLS
    LOCATE 1, 1: COLOR 15
    'INPUT "Enter number of Sweeps  ", sweepend
    INPUT " Enter the Relative humidity  ", RH
    INPUT " Enter the Temperature in F   ", H


10
3                       LOCATE 8, 1: COLOR 10
                       PRINT USING "\           \ ####   \
\"; "SAMPLE_ID"; sampleid; "    Processing  "
'   Instructions
    FOR sweep = 1 TO 2
```

```
        SLEEP 2
        stepa = .01
        starta = .01
        stopa = .09
        numbfreq = ((stopa - starta) / stepa) + 1
        PRINT , numbfreq
        DevName$ = DEV
        device% = InitMeter%(DevName$)
        CALL ReadIDString(device%)
            Cmd$ = "A2B3F1V1C3"
            LOCATE 15, 60: PRINT Cmd$
        CALL WriteCommand(device%, Cmd$)
            Cmd$ = "SF" + LTRIM$(STR$(stepa)) + "EN" + "TF" +
LTRIM$(STR$(starta)) + "EN" + "PF" + LTRIM$(STR$(stopa)) + "EN"
        CALL WriteCommand(device%, Cmd$)
            LOCATE 15, 30: PRINT Cmd$
            Cmd$ = "W1 W2"
            LOCATE 16, 1: PRINT "Sweep Number"; sweep
        CALL WriteCommand(device%, Cmd$)
            Cmd$ = "EX"
        CALL WriteCommand(device%, Cmd$)
        PRINT #2, sampleid$, RH, H, TT$, sweep,
        FOR C = 1 TO numbfreq
            TakeMeasurement (device%)
        NEXT C


' ****************** end of first cycle *****************************
SLEEP 2
        stepa = .1
        starta = .1
        stopa = .9
        numbfreq = ((stopa - starta) / stepa) + 1
        PRINT , numbfreq
        DevName$ = DEV
        device% = InitMeter%(DevName$)
        CALL ReadIDString(device%)
            Cmd$ = "A2B3F1V1C3"
            LOCATE 15, 60: PRINT Cmd$
        CALL WriteCommand(device%, Cmd$)
            Cmd$ = "SF" + LTRIM$(STR$(stepa)) + "EN" + "TF" +
LTRIM$(STR$(starta)) + "EN" + "PF" + LTRIM$(STR$(stopa)) + "EN"
        CALL WriteCommand(device%, Cmd$)
            LOCATE 15, 30: PRINT Cmd$
            Cmd$ = "W1 W2"
            LOCATE 16, 1: PRINT "Sweep Number"; sweep
        CALL WriteCommand(device%, Cmd$)
            Cmd$ = "EX"
        CALL WriteCommand(device%, Cmd$)
'        PRINT #2, sampleid$, RH, H, TT$, sweep,
        FOR C = 1 TO numbfreq
            TakeMeasurement (device%)
        NEXT C
'******************  End of the second cycle ************************
        SLEEP 2
```

```
        stepa = 1
        starta = 1
        stopa = 9
         numbfreq = ((stopa - starta) / stepa) + 1
        DevName$ = DEV
        device% = InitMeter%(DevName$)
        CALL ReadIDString(device%)
            Cmd$ = "A2B3F1V1C3"
            LOCATE 15, 60: PRINT Cmd$
        CALL WriteCommand(device%, Cmd$)
            Cmd$ = "SF" + LTRIM$(STR$(stepa)) + "EN" + "TF" +
LTRIM$(STR$(starta)) + "EN" + "PF" + LTRIM$(STR$(stopa)) + "EN"
        CALL WriteCommand(device%, Cmd$)
            LOCATE 15, 30: PRINT Cmd$
            Cmd$ = "W1 W2"
            LOCATE 16, 1: PRINT "Sweep Number"; sweep
        CALL WriteCommand(device%, Cmd$)
            Cmd$ = "EX"
        CALL WriteCommand(device%, Cmd$)
        FOR C = 1 TO numbfreq
        TakeMeasurement (device%)
        NEXT C
' ****************** End of 3rd cycle ******************************

        SLEEP 2
        stepa = 10
        starta = 10
        stopa = 90
        numbfreq = ((stopa - starta) / stepa) + 1
        DevName$ = DEV
        device% = InitMeter%(DevName$)
        CALL ReadIDString(device%)
            Cmd$ = "A2B3F1V1C3"
            LOCATE 15, 60: PRINT Cmd$
        CALL WriteCommand(device%, Cmd$)
            Cmd$ = "SF" + LTRIM$(STR$(stepa)) + "EN" + "TF" +
LTRIM$(STR$(starta)) + "EN" + "PF" + LTRIM$(STR$(stopa)) + "EN"
        CALL WriteCommand(device%, Cmd$)
            LOCATE 15, 30: PRINT Cmd$
            Cmd$ = "W1 W2"
            LOCATE 16, 1: PRINT "Sweep Number"; sweep
        CALL WriteCommand(device%, Cmd$)
            Cmd$ = "EX"
        CALL WriteCommand(device%, Cmd$)
        FOR C = 1 TO numbfreq
        TakeMeasurement (device%)
        NEXT C

' ********************* End of 3rd cycle ***************************

        SLEEP 2
        stepa = 100
        starta = 100
        stopa = 900
         numbfreq = ((stopa - starta) / stepa) + 1
```

```
        DevName$ = DEV
        device% = InitMeter%(DevName$)
        CALL ReadIDString(device%)
            Cmd$ = "A2B3F1V1C3"
            LOCATE 15, 60: PRINT Cmd$
        CALL WriteCommand(device%, Cmd$)
            Cmd$ = "SF" + LTRIM$(STR$(stepa)) + "EN" + "TF" +
LTRIM$(STR$(starta)) + "EN" + "PF" + LTRIM$(STR$(stopa)) + "EN"
        CALL WriteCommand(device%, Cmd$)
            LOCATE 15, 30: PRINT Cmd$
            Cmd$ = "W1 W2"
            LOCATE 16, 1: PRINT "Sweep Number"; sweep
        CALL WriteCommand(device%, Cmd$)
            Cmd$ = "EX"
        CALL WriteCommand(device%, Cmd$)
        FOR C = 1 TO numbfreq
        TakeMeasurement (device%)
        NEXT C
' ********************** End of 4rth cycle ************************

        SLEEP 2
        stepa = 1000
        starta = 1000
        stopa = 9000
         numbfreq = ((stopa - starta) / stepa) + 1
        DevName$ = DEV
        device% = InitMeter%(DevName$)
        CALL ReadIDString(device%)
            Cmd$ = "A2B3F1V1C3"
            LOCATE 15, 60: PRINT Cmd$
        CALL WriteCommand(device%, Cmd$)
            Cmd$ = "SF" + LTRIM$(STR$(stepa)) + "EN" + "TF" +
LTRIM$(STR$(starta)) + "EN" + "PF" + LTRIM$(STR$(stopa)) + "EN"
        CALL WriteCommand(device%, Cmd$)
            LOCATE 15, 30: PRINT Cmd$
            Cmd$ = "W1 W2"
            LOCATE 16, 1: PRINT "Sweep Number"; sweep
        CALL WriteCommand(device%, Cmd$)
            Cmd$ = "EX"
        CALL WriteCommand(device%, Cmd$)
        FOR C = 1 TO numbfreq
        TakeMeasurement (device%)
        NEXT C
' *************************** End of 5th cycle  *********************

        SLEEP 2
        numbfreq = 4
        stepa = 1000
        starta = 10000
        stopa = 13000
         numbfreq = ((stopa - starta) / stepa) + 1
        DevName$ = DEV
        device% = InitMeter%(DevName$)
        CALL ReadIDString(device%)
            Cmd$ = "A2B3F1V1C3"
```

```
            LOCATE 15, 60: PRINT Cmd$
        CALL WriteCommand(device%, Cmd$)
            Cmd$ = "SF" + LTRIM$(STR$(stepa)) + "EN" + "TF" +
LTRIM$(STR$(starta)) + "EN" + "PF" + LTRIM$(STR$(stopa)) + "EN"
        CALL WriteCommand(device%, Cmd$)
            LOCATE 15, 30: PRINT Cmd$
            Cmd$ = "W1 W2"
            LOCATE 16, 1: PRINT "Sweep Number"; sweep
        CALL WriteCommand(device%, Cmd$)
            Cmd$ = "EX"
        CALL WriteCommand(device%, Cmd$)
        FOR C = 1 TO numbfreq
        TakeMeasurement (device%)
        NEXT C

' ********************** End of 7th cycle ***********************
' *********************  End of measurements *********************

PRINT #2, "END_OF_SWEEP"
NEXT sweep

'**********************************************************************
    BEEP
    SLEEP 2
    BEEP
    SLEEP 2
    BEEP
'
    LOCATE 23, 1: COLOR 10
    INPUT "Do you wish to run another sample measurement Y/N", a$
    LOCATE 23, 1
    PRINT "
"
        IF a$ = "y" THEN a$ = "Y"
        IF a$ = "n" THEN a$ = "N"
        IF a$ = "N" THEN
           GOTO 2
            ELSE
            TT$ = "Sample"
            GOTO 102
            END IF
'
'***********************************************************************
' ********************** Open circuit **********************************
95
'*******************************************************************
    LOCATE 9, 1: COLOR 15
'     PRINT #2, DATE$, TIME$,
   PRINT #2, filename$
  PRINT #2, "sampleid", "RH", "Temp", "Mode", "sweep",
          u = .01
18      FOR i = 1 TO 9
            F = u * i
            IF F <= 10000 THEN
            PRINT #2, "G" + LTRIM$(STR$(F)), "B" + LTRIM$(STR$(F)),
```

```
            ELSE GOTO 19
            END IF
       NEXT i
            u = F + F / 9
            GOTO 18
19     FOR j = 11 TO 13
            F = j * 1000
            PRINT #2, "G" + LTRIM$(STR$(F)), "B" + LTRIM$(STR$(F)),
        NEXT j

        PRINT #2, "END_OF_LINE"

202 INPUT " Enter sample_ID", sampleid$
    LOCATE 23, 1: COLOR 10
    INPUT "Are you sure this is the correct sample ? Y/N", C$
    LOCATE 23, 1
    PRINT "                                                        "
                IF C$ = "n" THEN C$ = "N"
                IF C$ = "y" THEN C$ = "Y"
                    IF C$ = "Y" THEN
                    GOTO 115
               ELSE
                GOTO 202
    END IF
115
31 CLS
    LOCATE 1, 1: COLOR 15
'    INPUT "Enter number of Sweeps  ", sweepend
    INPUT " Enter the Relative humidity  ", RH
    INPUT " Enter the Temperature in F   ", H


33
34                        LOCATE 8, 1: COLOR 10
                         PRINT USING "\           \ ####   \
\"; "SAMPLE_ID"; sampleid; "    Processing  "
'   Instructions
    FOR sweep = 1 TO 2
        SLEEP 2
        stepa = .01
        starta = .01
        stopa = .09
        numbfreq = ((stopa - starta) / stepa) + 1
        PRINT , numbfreq
        DevName$ = DEV
        device% = InitMeter%(DevName$)
        CALL ReadIDString(device%)
            Cmd$ = "A2B3F1V1C3"
            LOCATE 15, 60: PRINT Cmd$
        CALL WriteCommand(device%, Cmd$)
            Cmd$ = "SF" + LTRIM$(STR$(stepa)) + "EN" + "TF" +
LTRIM$(STR$(starta)) + "EN" + "PF" + LTRIM$(STR$(stopa)) + "EN"
        CALL WriteCommand(device%, Cmd$)
            LOCATE 15, 30: PRINT Cmd$
            Cmd$ = "W1 W2"
```

```
            LOCATE 16, 1: PRINT "Sweep Number"; sweep
        CALL WriteCommand(device%, Cmd$)
            Cmd$ = "EX"
        CALL WriteCommand(device%, Cmd$)
        PRINT #2, sampleid$, RH, H, TT$, sweep,
        FOR C = 1 TO numbfreq
            TakeMeasurement (device%)
        NEXT C
SLEEP 2
        stepa = .1
        starta = .1
        stopa = .9
        numbfreq = ((stopa - starta) / stepa) + 1
        PRINT , numbfreq
        DevName$ = DEV
        device% = InitMeter%(DevName$)
        CALL ReadIDString(device%)
            Cmd$ = "A2B3F1V1C3"
            LOCATE 15, 60: PRINT Cmd$
        CALL WriteCommand(device%, Cmd$)
            Cmd$ = "SF" + LTRIM$(STR$(stepa)) + "EN" + "TF" +
LTRIM$(STR$(starta)) + "EN" + "PF" + LTRIM$(STR$(stopa)) + "EN"
        CALL WriteCommand(device%, Cmd$)
            LOCATE 15, 30: PRINT Cmd$
            Cmd$ = "W1 W2"
            LOCATE 16, 1: PRINT "Sweep Number"; sweep
        CALL WriteCommand(device%, Cmd$)
            Cmd$ = "EX"
        CALL WriteCommand(device%, Cmd$)
 '       PRINT #2, sampleid$, RH, H, TT$, sweep,
        FOR C = 1 TO numbfreq
            TakeMeasurement (device%)
        NEXT C
'
        SLEEP 2
        stepa = 1
        starta = 1
        stopa = 9
         numbfreq = ((stopa - starta) / stepa) + 1
        DevName$ = DEV
        device% = InitMeter%(DevName$)
        CALL ReadIDString(device%)
            Cmd$ = "A2B3F1V1C3"
            LOCATE 15, 60: PRINT Cmd$
        CALL WriteCommand(device%, Cmd$)
            Cmd$ = "SF" + LTRIM$(STR$(stepa)) + "EN" + "TF" +
LTRIM$(STR$(starta)) + "EN" + "PF" + LTRIM$(STR$(stopa)) + "EN"
        CALL WriteCommand(device%, Cmd$)
            LOCATE 15, 30: PRINT Cmd$
            Cmd$ = "W1 W2"
            LOCATE 16, 1: PRINT "Sweep Number"; sweep
        CALL WriteCommand(device%, Cmd$)
            Cmd$ = "EX"
        CALL WriteCommand(device%, Cmd$)
        FOR C = 1 TO numbfreq
```

```
        TakeMeasurement (device%)
        NEXT C
'

        SLEEP 2
        stepa = 10
        starta = 10
        stopa = 90
         numbfreq = ((stopa - starta) / stepa) + 1
        DevName$ = DEV
        device% = InitMeter%(DevName$)
        CALL ReadIDString(device%)
            Cmd$ = "A2B3F1V1C3"
            LOCATE 15, 60: PRINT Cmd$
        CALL WriteCommand(device%, Cmd$)
            Cmd$ = "SF" + LTRIM$(STR$(stepa)) + "EN" + "TF" +
LTRIM$(STR$(starta)) + "EN" + "PF" + LTRIM$(STR$(stopa)) + "EN"
        CALL WriteCommand(device%, Cmd$)
            LOCATE 15, 30: PRINT Cmd$
            Cmd$ = "W1 W2"
            LOCATE 16, 1: PRINT "Sweep Number"; sweep
        CALL WriteCommand(device%, Cmd$)
            Cmd$ = "EX"
        CALL WriteCommand(device%, Cmd$)
        FOR C = 1 TO numbfreq
        TakeMeasurement (device%)
        NEXT C

'

        SLEEP 2
        stepa = 100
        starta = 100
        stopa = 900
         numbfreq = ((stopa - starta) / stepa) + 1
        DevName$ = DEV
        device% = InitMeter%(DevName$)
        CALL ReadIDString(device%)
            Cmd$ = "A2B3F1V1C3"
            LOCATE 15, 60: PRINT Cmd$
        CALL WriteCommand(device%, Cmd$)
            Cmd$ = "SF" + LTRIM$(STR$(stepa)) + "EN" + "TF" +
LTRIM$(STR$(starta)) + "EN" + "PF" + LTRIM$(STR$(stopa)) + "EN"
        CALL WriteCommand(device%, Cmd$)
            LOCATE 15, 30: PRINT Cmd$
            Cmd$ = "W1 W2"
            LOCATE 16, 1: PRINT "Sweep Number"; sweep
        CALL WriteCommand(device%, Cmd$)
            Cmd$ = "EX"
        CALL WriteCommand(device%, Cmd$)
        FOR C = 1 TO numbfreq
        TakeMeasurement (device%)
        NEXT C
```

```
        SLEEP 2
        stepa = 1000
        starta = 1000
        stopa = 9000
         numbfreq = ((stopa - starta) / stepa) + 1
        DevName$ = DEV
        device% = InitMeter%(DevName$)
        CALL ReadIDString(device%)
            Cmd$ = "A2B3F1V1C3"
            LOCATE 15, 60: PRINT Cmd$
        CALL WriteCommand(device%, Cmd$)
            Cmd$ = "SF" + LTRIM$(STR$(stepa)) + "EN" + "TF" +
LTRIM$(STR$(starta)) + "EN" + "PF" + LTRIM$(STR$(stopa)) + "EN"
        CALL WriteCommand(device%, Cmd$)
            LOCATE 15, 30: PRINT Cmd$
            Cmd$ = "W1 W2"
            LOCATE 16, 1: PRINT "Sweep Number"; sweep
        CALL WriteCommand(device%, Cmd$)
            Cmd$ = "EX"
        CALL WriteCommand(device%, Cmd$)
        FOR C = 1 TO numbfreq
        TakeMeasurement (device%)
        NEXT C

        SLEEP 2
        numbfreq = 4
        stepa = 1000
        starta = 10000
        stopa = 13000
         numbfreq = ((stopa - starta) / stepa) + 1
        DevName$ = DEV
        device% = InitMeter%(DevName$)
        CALL ReadIDString(device%)
            Cmd$ = "A2B3F1V1C3"
            LOCATE 15, 60: PRINT Cmd$
        CALL WriteCommand(device%, Cmd$)
            Cmd$ = "SF" + LTRIM$(STR$(stepa)) + "EN" + "TF" +
LTRIM$(STR$(starta)) + "EN" + "PF" + LTRIM$(STR$(stopa)) + "EN"
        CALL WriteCommand(device%, Cmd$)
            LOCATE 15, 30: PRINT Cmd$
            Cmd$ = "W1 W2"
            LOCATE 16, 1: PRINT "Sweep Number"; sweep
        CALL WriteCommand(device%, Cmd$)
            Cmd$ = "EX"
        CALL WriteCommand(device%, Cmd$)
        FOR C = 1 TO numbfreq
        TakeMeasurement (device%)
        NEXT C


' **************   End of measurements ********************************
        PRINT #2, "END_OF_SWEEP"

    NEXT sweep
'**********************************************************************
```

```
    BEEP
    SLEEP 2
    BEEP
    SLEEP 2
    BEEP
'CLOSE #2
    LOCATE 23, 1: COLOR 10
    INPUT "Do you wish to run another open circuit measurement Y/N", a$
    LOCATE 23, 1
    PRINT "
"
        IF a$ = "y" THEN a$ = "Y"
        IF a$ = "n" THEN a$ = "N"
        IF a$ = "N" THEN
           GOTO 2
            ELSE
            TT$ = "Open"
            GOTO 202
            END IF
'************************************************************************
'**********    Short Circuit measurements    *************************
'*********************************************************************
75
CLS
'********************************************************************
    LOCATE 9, 1: COLOR 15
    PRINT #2, DATE$, TIME$,
    PRINT #2, filename$
    PRINT #2, "sampleid", " RH", "Temp", "Mode", "sweep",
            u = .01
            LOCATE 13, 1: COLOR 10
14      FOR i = 1 TO 9
            F = u * i
            IF F <= 10000 THEN
            PRINT #2, "R" + LTRIM$(STR$(F)), "X" + LTRIM$(STR$(F)),
            ELSE GOTO 16
            END IF
       NEXT i
            u = F + F / 9
            GOTO 14
16      FOR j = 11 TO 13
            F = j * 1000
            PRINT #2, "R" + LTRIM$(STR$(F)), "X" + LTRIM$(STR$(F)),
        NEXT j

        PRINT #2, "END_OF_LINE"
40 CLS
    LOCATE 1, 1: COLOR 15
    INPUT " Enter sample Id", sampleid$
'    INPUT "Enter number of Sweeps   ", sweepend
    INPUT " Enter the Relative humidity   ", RH
    INPUT " Enter the Temperature in F   ", H
'**********************************************************************
    LOCATE 23, 1: COLOR 10
    INPUT "Are you sure this is the correct sample ? Y/N", C$
```

```
    LOCATE 23, 1
    PRINT "                                                                  "
                IF C$ = "n" THEN C$ = "N"
                IF C$ = "y" THEN C$ = "Y"
                    IF C$ = "Y" THEN
                    GOTO 32
                ELSE
                GOTO 40
    END IF
32

22
7                       LOCATE 8, 1: COLOR 10
                        PRINT USING "\            \ ####    \
\"; "SAMPLE_ID"; sampleid; "    Processing  "
'   Instructions
    FOR sweep = 1 TO 2
        SLEEP 2
        stepa = .01
        starta = .01
        stopa = .09
        numbfreq = ((stopa - starta) / stepa) + 1
        PRINT , numbfreq
        DevName$ = DEV
        device% = InitMeter%(DevName$)
        CALL ReadIDString(device%)
            Cmd$ = "A2B3F1V1C3"
            LOCATE 15, 60: PRINT Cmd$
        CALL WriteCommand(device%, Cmd$)
            Cmd$ = "SF" + LTRIM$(STR$(stepa)) + "EN" + "TF" +
LTRIM$(STR$(starta)) + "EN" + "PF" + LTRIM$(STR$(stopa)) + "EN"
        CALL WriteCommand(device%, Cmd$)
            LOCATE 15, 30: PRINT Cmd$
            Cmd$ = "W1 W2"
            LOCATE 16, 1: PRINT "Sweep Number"; sweep
        CALL WriteCommand(device%, Cmd$)
            Cmd$ = "EX"
        CALL WriteCommand(device%, Cmd$)
        PRINT #2, sampleid$, RH, H, TT$, sweep,
        FOR C = 1 TO numbfreq
            TakeMeasurement (device%)
        NEXT C

        stepa = .1
        starta = .1
        stopa = .9
        numbfreq = ((stopa - starta) / stepa) + 1
        PRINT , numbfreq
        DevName$ = DEV
        device% = InitMeter%(DevName$)
        CALL ReadIDString(device%)
            Cmd$ = "A2B3F1V1C2"
            LOCATE 15, 60: PRINT Cmd$
        CALL WriteCommand(device%, Cmd$)
```

```
            Cmd$ = "SF" + LTRIM$(STR$(stepa)) + "EN" + "TF" +
LTRIM$(STR$(starta)) + "EN" + "PF" + LTRIM$(STR$(stopa)) + "EN"
        CALL WriteCommand(device%, Cmd$)
            LOCATE 15, 30: PRINT Cmd$
            Cmd$ = "W1 W2"
            LOCATE 16, 1: PRINT "Sweep Number"; sweep
        CALL WriteCommand(device%, Cmd$)
            Cmd$ = "EX"
        CALL WriteCommand(device%, Cmd$)
'        PRINT #2, sampleid$, RH, H, TT$, sweep,
        FOR C = 1 TO numbfreq
            TakeMeasurement (device%)
        NEXT C
'
        SLEEP 2
        stepa = 1
        starta = 1
        stopa = 9
         numbfreq = ((stopa - starta) / stepa) + 1
        DevName$ = DEV
        device% = InitMeter%(DevName$)
        CALL ReadIDString(device%)
            Cmd$ = "A2B3F1V1C2"
            LOCATE 15, 60: PRINT Cmd$
        CALL WriteCommand(device%, Cmd$)
            Cmd$ = "SF" + LTRIM$(STR$(stepa)) + "EN" + "TF" +
LTRIM$(STR$(starta)) + "EN" + "PF" + LTRIM$(STR$(stopa)) + "EN"
        CALL WriteCommand(device%, Cmd$)
            LOCATE 15, 30: PRINT Cmd$
            Cmd$ = "W1 W2"
            LOCATE 16, 1: PRINT "Sweep Number"; sweep
        CALL WriteCommand(device%, Cmd$)
            Cmd$ = "EX"
        CALL WriteCommand(device%, Cmd$)
        FOR C = 1 TO numbfreq
        TakeMeasurement (device%)
        NEXT C
'
        SLEEP 2
        stepa = 10
        starta = 10
        stopa = 90
         numbfreq = ((stopa - starta) / stepa) + 1
        DevName$ = DEV
        device% = InitMeter%(DevName$)
        CALL ReadIDString(device%)
            Cmd$ = "A2B3F1V1C2"
            LOCATE 15, 60: PRINT Cmd$
        CALL WriteCommand(device%, Cmd$)
            Cmd$ = "SF" + LTRIM$(STR$(stepa)) + "EN" + "TF" +
LTRIM$(STR$(starta)) + "EN" + "PF" + LTRIM$(STR$(stopa)) + "EN"
        CALL WriteCommand(device%, Cmd$)
            LOCATE 15, 30: PRINT Cmd$
            Cmd$ = "W1 W2"
            LOCATE 16, 1: PRINT "Sweep Number"; sweep
```

```
        CALL WriteCommand(device%, Cmd$)
            Cmd$ = "EX"
        CALL WriteCommand(device%, Cmd$)
        FOR C = 1 TO numbfreq
        TakeMeasurement (device%)
        NEXT C



        SLEEP 2
        stepa = 100
        starta = 100
        stopa = 900
         numbfreq = ((stopa - starta) / stepa) + 1
        DevName$ = DEV
        device% = InitMeter%(DevName$)
        CALL ReadIDString(device%)
            Cmd$ = "A2B3F1V1C2"
            LOCATE 15, 60: PRINT Cmd$
        CALL WriteCommand(device%, Cmd$)
            Cmd$ = "SF" + LTRIM$(STR$(stepa)) + "EN" + "TF" +
LTRIM$(STR$(starta)) + "EN" + "PF" + LTRIM$(STR$(stopa)) + "EN"
        CALL WriteCommand(device%, Cmd$)
            LOCATE 15, 30: PRINT Cmd$
            Cmd$ = "W1 W2"
            LOCATE 16, 1: PRINT "Sweep Number"; sweep
        CALL WriteCommand(device%, Cmd$)
            Cmd$ = "EX"
        CALL WriteCommand(device%, Cmd$)
        FOR C = 1 TO numbfreq
        TakeMeasurement (device%)
        NEXT C
'

        SLEEP 2
        stepa = 1000
        starta = 1000
        stopa = 9000
         numbfreq = ((stopa - starta) / stepa) + 1
        DevName$ = DEV
        device% = InitMeter%(DevName$)
        CALL ReadIDString(device%)
            Cmd$ = "A2B3F1V1C2"
            LOCATE 15, 60: PRINT Cmd$
        CALL WriteCommand(device%, Cmd$)
            Cmd$ = "SF" + LTRIM$(STR$(stepa)) + "EN" + "TF" +
LTRIM$(STR$(starta)) + "EN" + "PF" + LTRIM$(STR$(stopa)) + "EN"
        CALL WriteCommand(device%, Cmd$)
            LOCATE 15, 30: PRINT Cmd$
            Cmd$ = "W1 W2"
            LOCATE 16, 1: PRINT "Sweep Number"; sweep
        CALL WriteCommand(device%, Cmd$)
            Cmd$ = "EX"
        CALL WriteCommand(device%, Cmd$)
        FOR C = 1 TO numbfreq
```

```
        TakeMeasurement (device%)
        NEXT C
'

        SLEEP 2
        numbfreq = 4
        stepa = 1000
        starta = 10000
        stopa = 13000
         numbfreq = ((stopa - starta) / stepa) + 1
        DevName$ = DEV
        device% = InitMeter%(DevName$)
        CALL ReadIDString(device%)
            Cmd$ = "A2B3F1V1C2"
            LOCATE 15, 60: PRINT Cmd$
        CALL WriteCommand(device%, Cmd$)
            Cmd$ = "SF" + LTRIM$(STR$(stepa)) + "EN" + "TF" +
LTRIM$(STR$(starta)) + "EN" + "PF" + LTRIM$(STR$(stopa)) + "EN"
        CALL WriteCommand(device%, Cmd$)
            LOCATE 15, 30: PRINT Cmd$
            Cmd$ = "W1 W2"
            LOCATE 16, 1: PRINT "Sweep Number"; sweep
        CALL WriteCommand(device%, Cmd$)
            Cmd$ = "EX"
        CALL WriteCommand(device%, Cmd$)
        FOR C = 1 TO numbfreq
        TakeMeasurement (device%)
        NEXT C

'
' ****************    End of measurements ****************************
        PRINT #2, "END_OF_SWEEP"

    NEXT sweep
'**********************************************************************
    BEEP
    SLEEP 2
    BEEP
    SLEEP 2
    BEEP
'CLOSE #2
    LOCATE 23, 1: COLOR 10
    INPUT "Do you wish to run another short circuit Sample Y/N", a$
    LOCATE 23, 1
    PRINT "
"
        IF a$ = "y" THEN a$ = "Y"
        IF a$ = "n" THEN a$ = "N"
        IF a$ = "N" THEN
           GOTO 2
            ELSE
            TT$ = "Short"
            GOTO 40
            END IF
```

```
105  CLOSE #2
END

'************************************************************************
**
'
' Name:         InitMeter
' Arguments:    DevName - name of GPIB device
' Returns:      device handle of voltmeter
'
' Description: Opens the device, sets the system timeout to 3 seconds,
'              sends a reset command to the voltmeter.  Returns the GPIB
'              device handle.
'
'************************************************************************
**
FUNCTION InitMeter% (DevName$) STATIC
    CALL IBFIND(DevName$, device%)       ' Open the device
    IF device% < 0 AND IBERR% = EDVR THEN
        PRINT "IBFIND Couldn't find device "; DevName$
        PRINT "   Make sure that you have assigned the name"; DevName$;
"to the"
        PRINT "   meter with the CBCONF.EXE program.  Make sure that the
meter is"
        PRINT "   configured for the address that you specified with
CBCONF.EXE."
        END
    ELSEIF device% < 0 AND IBERR% = ECFG THEN
        PRINT "Board is not configured correctly"
        PRINT "   The board type that is set in GPIB.CFG file does not
match the"
        PRINT "   board that is installed.  Run the CBCONF.EXE program and
check"
        PRINT "   the board type that is set there and make sure it
matches the"
        PRINT "   board that you have installed in your system."
    END IF
'     dum = ILTMO(device%, T3s)

   IBSTA& = ILTMO%(device%, T5s)               ' Set the timeout

    CALL WriteCommand(device%, RESETCMD)     ' Send reset command
'     CALL WriteCommand(device%, RANGECMD)    ' Select Volts AC range
    InitMeter% = device%                     ' Return the device handle
END FUNCTION

'************************************************************************
**
'
' Name:         Instructions
' Arguments:    ---
'
' Description: Prints the programs instructions
'
```

```
'***********************************************************************
**
SUB Instructions STATIC
   CLS
   LOCATE 1, 20
   PRINT "QuickBASIC Example GPIB Program"
   LOCATE 3, 1
   PRINT "This is a program requires user input to communicate with an"
   PRINT "            4192A LF IMPEDANCE ANALYER 5Hz-13MHz"
   PRINT ""
   PRINT "The program expects that the 4192A LFIMPEDANCE ANALYER has
already been"
   PRINT "installed with the CBCONF.EXE program and been given the name
HO3 ."
   PRINT ""
   PRINT "                  --- Press any key to start ---"
   DO WHILE INKEY$ = ""
      LOOP

END SUB
```

```
'***********************************************************************
**
'
' Name:         PrintErrors
' Arguments:    ---
'
' Description: Prints the global GPIB status and error codes
'
'***********************************************************************
**
SUB PrintErrors (ErrStr$) STATIC

   PRINT CHR$(7);          ' Beep the speaker

   LOCATE 20, 1
   PRINT "    *** ERROR ***"; ErrStr$
   PRINT "    Error codes:  ibsta% = 0x"; HEX$(IBSTA%); " (";
   i = 0
   DO WHILE StatBits$(i) <> ""          ' Print names for status bits
      IF IBSTA% AND StatBits(i) THEN
         PRINT StatBits$(i); " ";
      END IF
      i = i + 1
   LOOP
   PRINT ")"
```

```
   LOCATE 22, 1
   PRINT SPACE$(70)
   LOCATE 22, 1
   PRINT "                  iberr% ="; IBERR%; " (";
   i = 1
   DO WHILE ErrCodes$(i) <> ""
      IF IBERR% = ErrCodes(i) THEN
         PRINT ErrCodes$(i); ")"
      END IF
      i = i + 1
   LOOP

   LOCATE 23, 1
   PRINT "                  ibcnt% ="; IBCNT%; "          "
END SUB

'*************************************************************************
**
'
' Name:          ReadIDString
' Arguments:     device% - GPIB device handle returned by ibfind
'
' Description: Sends commnd to volt meter that tells it to return its
'                identification string.  Prints the string on the screen
'
'*************************************************************************
**
SUB ReadIDString (device%) STATIC
  CALL WriteCommand(device%, IDCMD)               ' Send command
  IF ReadValue(device%, BUFFER$, BUFSIZE) = TRUE THEN   ' Read response
     LOCATE 14, 1
     PRINT "IMPEDANCE ANALYZER ID = "; 4192    ' Print response
  END IF
END SUB

'*************************************************************************
**
'
' Name:          ReadValue%
' Arguments:     device% - GPIB device handle returned by ibfind
'                rdbuf$ - String buffer for return value
'                bufsize - size of buffer
' Returns:       TRUE for success, FALSE if it fails
'                Fills up buffer$
'
' Description: Fills the string with spaces, Reads a string from the
'                GPIB device and checks for errors.
'
'*************************************************************************
**
FUNCTION ReadValue% (device%, rdbuf$, BUFSIZE%) STATIC
   rdbuf$ = STRING$(BUFSIZE - 1, NULLCHAR)   ' Clear string
   IBSTA% = ILRD%(device%, rdbuf$)               ' Read from GPIB
   IF (IBSTA% AND EERR) THEN                  ' Check for erros
      PrintErrors ("IBRD failed")
```

```
      ReadValue% = FALSE
   ELSE
      ReadValue% = TRUE
      i = 1
      DO WHILE MID$(rdbuf$, i, 1) <> CHR$(NULLCHAR)
         i = i + 1
         LOOP
      rdbuf$ = LEFT$(rdbuf$, i - 2)
   END IF
END FUNCTION

'**************************************************************************
**
'
' Name:         TakeMeasurement
' Arguments:    device% - GPIB device handle returned by ibfind
'
' Description: Sends a command to the voltmeter that tells it to take
'               a measurement and return it over the GPIB.  Reads the
'               measurement value and prints it on the screen.
'
'**************************************************************************
**
SUB TakeMeasurement (device%) STATIC
  CALL WriteCommand(device%, MEASURECMD)        ' Send command
  IF ReadValue%(device%, BUFFER$, BUFSIZE) = TRUE THEN     ' Read response
     LOCATE 17, 1: COLOR 15
 PRINT , " .... measurement progressing... "
    LOCATE 18, 1: COLOR 10
 PRINT "DISPLAY A  = "; MID$(BUFFER$, 5, 11) ' Print response
 PRINT "DISPLAY B  = "; MID$(BUFFER$, 22, 11) ' Print response
 PRINT "FREQUENCY ="; MID$(BUFFER$, 36, 10)
' PRINT #2, MID$(BUFFER$, 36, 10),

 PRINT #2, MID$(BUFFER$, 5, 11),
 PRINT #2, MID$(BUFFER$, 22, 11),


  END IF

END SUB

'**************************************************************************
**
'
' Name:         WriteCommand
' Arguments:    device% - GPIB device handle returned by ibfind
'               cmd$ - String containing command
'
' Description: Writes the command to the GPIB device and then checks for
'               errors.
'
'**************************************************************************
**
SUB WriteCommand (device%, Cmd$) STATIC
```

```
CALL IBWRT(device%, Cmd$)
   IF (IBSTA% AND EERR) THEN
      ErrStr$ = "IBWRT failed while writing " + Cmd$
      PrintErrors (ErrStr$)
   END IF
END SUB
```