# Fringing Field Capacitance Sensor for Measuring the Moisture Content of Agricultural Commodities

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***Abstract*—A fringing field capacitive sensor is described for measuring the moisture content (MC) and temperature of agricultural commodities. Sensor performance was characterized by mounting the device on handheld probes and in acrylic canisters to determine the dielectric constant and MC of wheat and corn. The handheld probes demonstrated a promising capability to measure the MC of grain in hoppers, truck beds, and cargo holds. It is proposed that the sensors be supported on cables in grain silos and storage bins to acquire *in situ* data for grain storage management and control of aeration systems. The sensor is watertight and constructed with corrosion resistant materials which allow MC measurements to be made of industrial materials, chemicals, and fuels.**

***Index Terms*—Capacitance sensor, dielectric constant, grain storage management, moisture content (MC), moisture sensor.**

## I. Introduction

THE design, operation, and construction are described for a low-cost, fringing field capacitive (FFC) transducer. The sensor has the capability to measure the moisture content (MC) and temperature of agricultural commodities. Sensor performance was characterized by measuring the static dielectric constant and MC of wheat, corn, and liquids.

Representative measurements were made with experimental FFC sensors mounted on handheld probes and in 1.5 liter canisters to determine their sensitivity to changes in MC for hard red wheat and yellow dent corn. Capacitance variations and corresponding moisture equivalent deviations were obtained for consecutive probe and canister measurements of wheat, for six values of MC. The measurements demonstrated the feasibility of using FFC sensors to determine the MC of grain temporarily stored in hoppers and transported in truck beds, and cargo holds. As is the case for existing commercial moisture meters, accurate MC measurements require the use of grain specific calibration data and corrections to be made for temperature and test weight.

Three methods are discussed for using cable-borne sensors to obtain continuous *in situ* MC and temperature measurements in bulk stored grain. These capabilities have the potential to provide enhanced data for grain storage management and control of aeration and grain drying systems.

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## II. Background

Capacitive-based moisture sensors operate on the principle that the dielectric constant (real part of permittivity) of a material matrix is dominated by the presence of free water, and to a lesser extent, by physically adsorbed and absorbed water. In grain, water is adsorbed on the porous surface of the kernels and absorbed within the tissues of grain [1]. Free water is present in wet grain as a multilayer film or condensate on the surface of the kernels.

The amount of water associated with porous and granular materials significantly affects the dielectric properties of the material. The dielectric constant of free water is 80.13 at 20 °C compared with the dielectric constant of grains and soils that generally fall in a range between 2–7 [2]. The high dielectric constant of water arises from the large dipole moment of its asymmetric molecules [3]. However, the polarizability of physically bonded water to grain in an electric field is less because the orientation of the molecular dipoles are constrained by competitive van der Waals type (electrostatic) bonding forces [4], [5]. The high bond strength of chemically bonded water to the constituents of grain contributes to the intrinsic dielectric constant of the material.

Accurate measurements of MC obtained by measuring the dielectric constant of a particulate matrix, e.g., grain or soil mixed with air and water, require that the temperature and bulk density of the material be known or measured [6].

Capacitive moisture meters are used in the U.S. and Canada to measure the MC of grain, rice, beans, peas, oil seeds, nuts, and processed foodstuffs for commerce and trade. Small samples of a commodity are measured in a cell of fixed volume with walls that include parallel-plate or concentric cylindrical electrodes. The capacitance of the cell determines the effective dielectric constant of the grain from which its MC is estimated using instrument specific calibration curves [7], [8]. However, these meters cannot be inserted into bulk materials or supported by cables in silos or storage bins.

Conventional grain moisture meters determine capacitance $C$ by measuring capacitive reactance $X_C = -1/(2\pi fC)$ in an ac bridge at excitation frequencies $f$ greater that 1 MHz. At lower frequencies, dissipation losses prevent reliable measurements to be made of materials with high MCs [9]. By contrast, the FFC sensor electronics measures capacitance at low repetition frequencies by determining its ability to store charge.

Commercial capacitive-based moisture sensors of limited performance are constructed with interdigitated electrodes on planar or cylindrical substrates [10], [11]. The electrode structure of these sensors can be electrically insulated by a thin, low-dielectric cover layer to prevent dc conduction between the electrodes through the measurement medium. A disadvantage

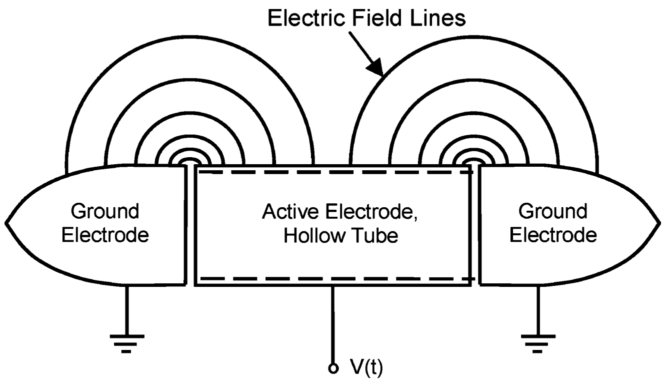


Fig. 1. Electrode arrangement for FFC sensor.

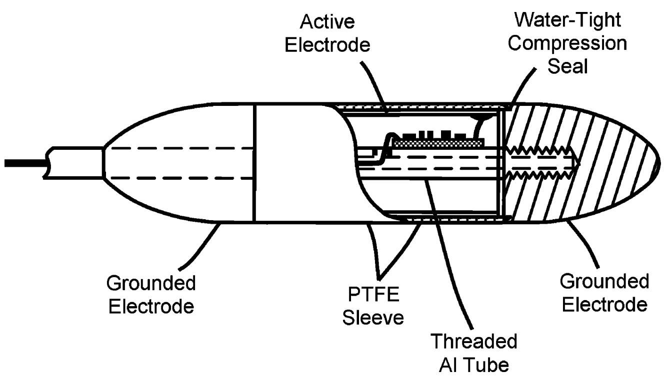


Fig. 2. Sensor assembly showing internal electronics PCB.

of interdigitated capacitive sensors is the small size and the narrow spacing of the electrode fingers. This restricts the region in which a measurement is made to a thin, material layer at the surface of the sensor; errors can occur when measuring granular materials [12].

## III. Transducer Design

### A. Construction

The FFC moisture sensor comprises three, cylindrical electrodes aligned along a common axis, as shown in Fig. 1. An active capacitor electrode is located between two electrically grounded electrodes; air gaps are maintained between the electrodes. The active capacitance of a sensor arises from fringing electric fields that couple electrical charge of opposing polarity distributed on the external surfaces of the electrodes. The field lines (lines of electrostatic force of attraction) are represented by two, nested sets of lines. At progressively further distances along the cylinder from the electrode gaps, the field lines travel over longer paths to more distant sites on the grounded electrodes, thereby penetrating deeper into the surrounding medium.

The active electrode is an electrically conducting metal tube filled with air. Small air gaps are maintained between the grounded end-cap electrodes and the annular faces of the active electrode. A PTFE fluoropolymer insulating sleeve is placed over the active electrode to avoid leakage current between the cooperating electrodes, as shown in Fig. 2.

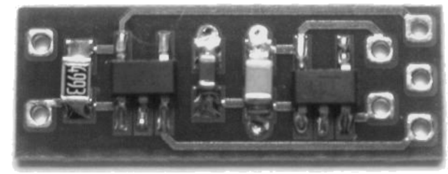

Fig. 3. Capacitance and temperature sensing electronics on a 19-mm long by 7-mm wide PCB with a surface-mount thermistor chip.

The PTFE sleeve spans the two capacitor gaps, and its end walls are tapered to mate with grooves in the grounded electrodes to form watertight, pressure seals. These electrodes can be fabricated from anodized aluminum or stainless steel to provide a chemical and abrasion resistant assembly.

In dry air, the capacitance of a sensor with an active electrode, 38.1 mm long by 15.9 mm in diameter is typically 12 pF. When the sensor is inserted in grain or soil, the majority of its capacitance is associated with the higher dielectric constant of the surrounding medium. Shunt capacitance arising from field coupling through air from the interior surface of the active electrode is comparatively small. The capacitance sensitivity of the sensor is defined as the change in capacitance $\Delta\mathrm{C}$, due to a change in the dielectric constant $\Delta\varepsilon'$ of the surrounding medium.

Values of $\Delta\mathrm{C}/\Delta\varepsilon'$ and $\Delta\mathrm{C}/\Delta\mathrm{MC}$ for the sensor are high compared with capacitive sensors with interdigitated electrodes. The capacitive sensitivity of interdigitated capacitors fabricated on hollow cylindrical PTFE and planar polyimide substrates were found to be 6–8 times lower than the FFC sensors of comparable size [13]. The high capacitance and sensitivity of the FFC sensor is primarily due its large electrodes and deeper penetration of the electrical field in the measurement medium. However, the field is unaffected by grounded objects located 6–8 cm from the sensor.

### B. Electronics

Many circuits exist to measure capacitance [9]. The large capacitance values of the FFC sensor allowed a simple, low-cost circuit to be used that has the accuracy and stability required for precision MC measurements. The electronics shown in Fig. 3 comprise a small, surface-mount, printed circuit board (PCB) with two RC relaxation oscillators; one measures capacitance and the other temperature.

A relaxation oscillator has an output frequency that corresponds to the time required to periodically charge and discharge a capacitor $C_t$ through a timing resistor $R_t$ [14]. The sensor serves as $C_t$ in the first oscillator. The RC components of the second oscillator comprise a thermistor chip or bead and a temperature compensated ceramic COG capacitor. An advantage of providing a frequency output is that it can be transmitted over long cable lengths before conversion by a digital counter circuit for data logging. The power consumption of the electronics is 3.2 mW at 5 VDC.

The temperature coefficients of timing resistor $R_t$ and the COG capacitor are $\pm 25$ ppm/°C and $\pm 15$ ppm/°C respectively, over a temperature range of 10 °C–40 °C. The sensor's active electrode is connected to commonly connected threshold and trigger inputs of a miniature, MIC 1557, CMOS timer IC.

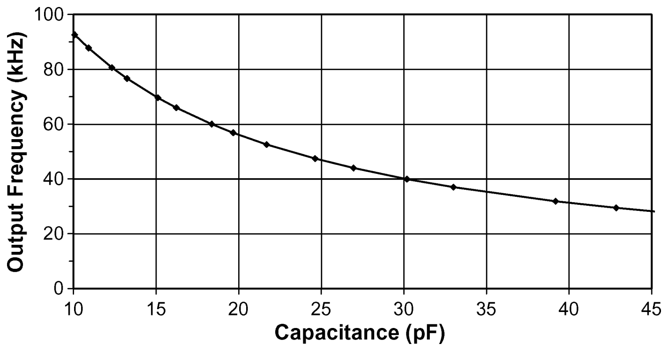


Fig. 4. Calibration curve used to convert the output frequency of FFC sensors to capacitance.

Sensors can use a miniature thermistor bead to provide fast temperature measurements. A thermistor mounted in an epoxy well in an end-cap electrode was found to have a thermal time constant of 3–5 s in wheat.

The output frequency of a CMOS relaxation oscillator is not linear for small RC time constants. The capacitive response of the FFC sensor with a 470 $k\Omega$, precision 0.05%, resistor is shown in Fig. 4. This curve was plotted by inserting radial lead, COG ceramic capacitors into pin sockets placed in the capacitor input wire-points on left side of the PCB in Fig. 3. The capacitor leads were cut to a length of 2.5 mm, and the capacitors measured using a HP 4275A LCR meter, a HP 16047A test fixture, and a custom adaptor with identically spaced pin sockets as those on the electronics PCB.

The curve of Fig. 4 can be represented by a reciprocal equation of the form

$$f = \frac{1}{a \cdot C + b} \tag{1}$$

where $f$ is the sensor output frequency (kHz) and $C$ is sensor capacitance (pF). Constants $a = 0.000707$ and $b = 0.003694$. The rms variation between (1) and the measured calibration data used to plot the curve of Fig. 4 is 0.0121 kHz. This value corresponds to an rms capacitance error of 0.026%. By comparison, the output frequency variation of a sensor operating at 5 VDC is typically 0.0025% (rms).

For research, more accurate electronics exist to measure the ability of a capacitor to store charge. In one circuit, a capacitor is placed in a bridge circuit with a reference capacitor and the bridge is actively nulled by current feedback to provide a linear output over a wide dynamic range [15], [16].

## IV. Measurement Methods

### A. Moisture

FFC sensors were mounted in two configurations to measure the MC of wheat and corn: on handheld probes (Fig. 5) and in 1.5 liter acrylic canisters (Fig. 6). The canister is shown mounted on a Seedburo, Model 8800A, Computer Grain Scale that can be used to measure the bulk density of the grain. The output frequency of the sensors were measured with a HP 53131A Universal Counter. Values of frequency were then converted to capacitance using (1).

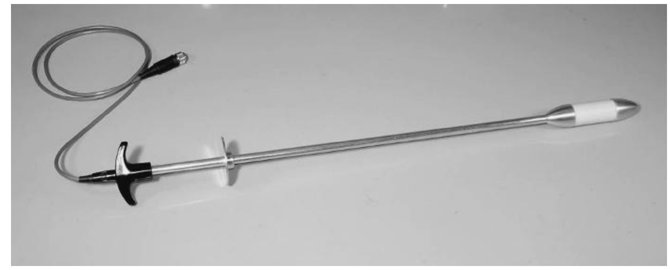

Fig. 5. Hand probe with a 9-cm long FFC sensor.

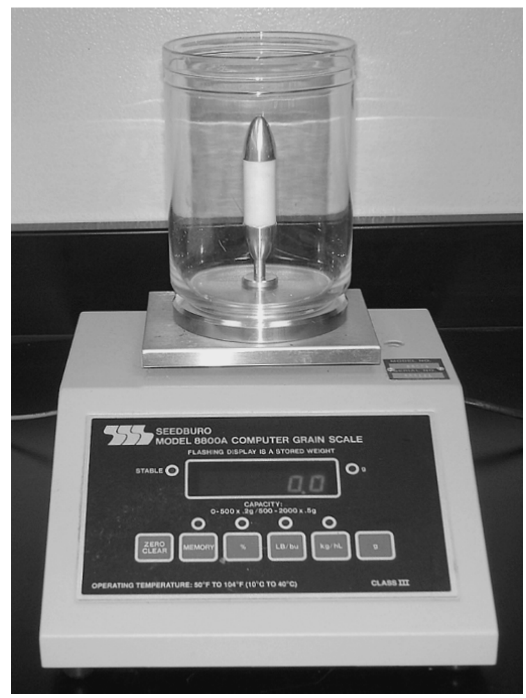


Fig. 6. A sensor mounted in a canister used to measure the MC of grain and the dielectric constant of fluids.

Measurements of the MC, wet basis (w.b.) of HRW wheat (cultivar: Endurance, KS 2006) and yellow dent corn (cultivar: Taylor KS, 2006) were made with probes and in canisters inside a walk-in, environmental chamber at the USDA, Grain Marketing and Production Research Center (GMPRC), Manhattan, KS. The chamber was controlled to 20 $\pm$ 1 °C. Earlier MC measurements were performed at Horizon Technology Group, Williamsburg, VA, along with measurements used to characterize the temperature response of the electronics and FFC sensors in canisters filled with air and wheat.

The MC of wheat and corn was measured by inserting the sensing probes to a depth of 30 cm into grain stored in PVC containers (20 cm diameter by 50 cm high) shown in Fig. 7. The MC of the samples was determined gravimetrically by the air-oven method, ASAE Standard S352.2 [17]. Two, 10-gram samples of grain were collected from each container before and after a measurement series with a partitioned grain probe. Each reported value of MC (w.b.) is an average value obtained from four, oven-dried measurements.

A Seedburo filling hopper and stand (Seedburo Equipment Company, Chicago, IL) were used to fill the canister from a

Fig. 7. PVC containers used to storage grain at different MCs.

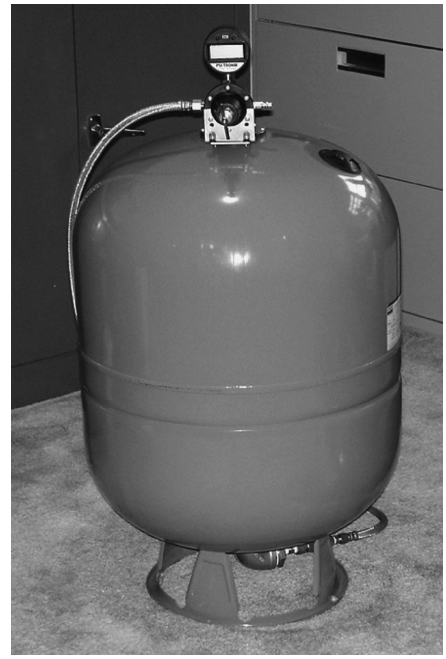

Fig. 8. Pressure expansion tank used to simulate overburden pressure in a grain storage silo.

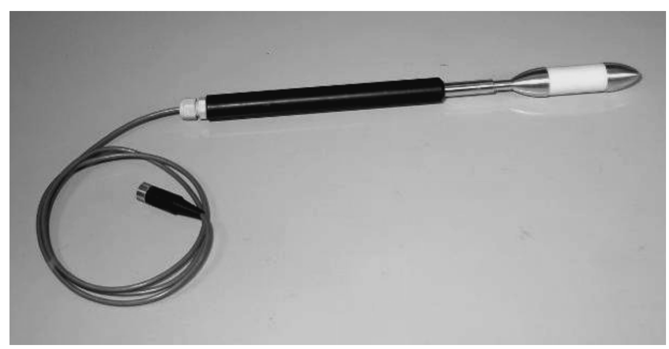

Fig. 9. Sensor probe used to measure the dielectric constant of grain in the pressure vessel.

height of 5 cm to obtain a loose, uniform packing density for 1.5 liter samples of grain.

The terms *loosely packed* and *settled* are used here to describe two general states of grain compaction. Grain poured freely into a canister or a PVC container is mechanically unstable. Small mechanical forces and vibration cause grain kernels to reorient which increases the bulk density of the grain. It was found that multiple insertions of a probe in a PVC container filled with freshly poured grain caused it to compact. The capacitance of a sensing probe increased with consecutive insertions before a stable value was reached after 10–16 measurements. This phenomenon was avoided by tamping the grain after it was poured into a container by tapping the side of the container three times with a rubber mallet.

Grain in hoppers, trucks and cargo holds undergoes a degree of settling due to mechanical vibration. Measurements are currently being made of grain compaction in truck beds for different driving distances and road conditions.

### B. Grain Compaction

An experimental apparatus was fabricated to demonstrate the ability of FFC sensors to measure the MC and bulk density of grain under overbearing pressure in silos and bins. A 102 liter (27 gal.) steel water-expansion tank with an internal rubber diaphragm was used to simulated overburden pressure. The tank, shown in Fig. 8, is inverted to place the water inlet side at the top. Grain and a sensing probe (Fig. 9) were inserted through a circular stainless-steel plate bolted to an expanded port at the top of the inverted tank.

After the tank was filled with 35 liters of wheat, air was pumped through a needle valve at the bottom of the tank to first elevate and then apply pressure to the diaphragm and grain. Compressed air was applied through a precision regulator with a pressure gauge having a NIST traceable accuracy of 0.1%. The tank has the capability to simulate the weight of a column of grain up to a height of 200 ft. (61 m).

## V. Measurement Results

### A. Wheat and Corn

Measurements were made with a sensor mounted on a probe and in a canister for six, MC samples of HRW wheat at 20 °C. Fig. 10 compares the capacitance response of the probe in settled kernels to the response of the sensor in a canister of loosely packed kernels.

Twenty-five measurements were made for each of the six samples of tamped wheat in PVC containers to study capacitance variations between consecutive probe insertions. The effect of the tamping method is shown by the uniform offset between the response curves of Fig. 10. The mean offset between the two curves is 1.1% for MC values up to 15%. It increased to 7.68% for the 17.2% MC wheat, presumably because of higher friction between moist kernels that required a larger push-in force to insert the probe.

The capacitance values for 25 probe measurements of wheat with three different MCs (7.6%, 10.4%, and 15.0%) are plotted

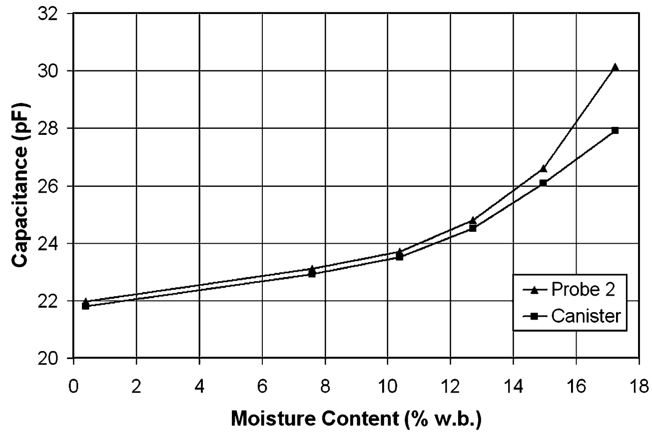


Fig. 10. Capacitance versus MC of HRW wheat obtained with a probe inserted into settled kernels and a sensor mounted in canister with loosely packed kernels.

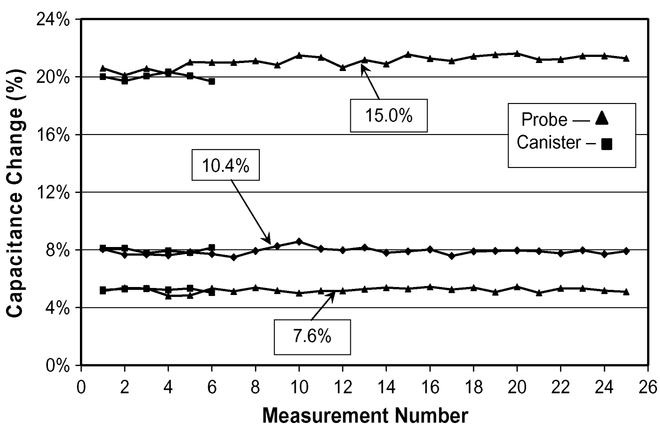


Fig. 11. Capacitance variations for HRW wheat at three moisture values.

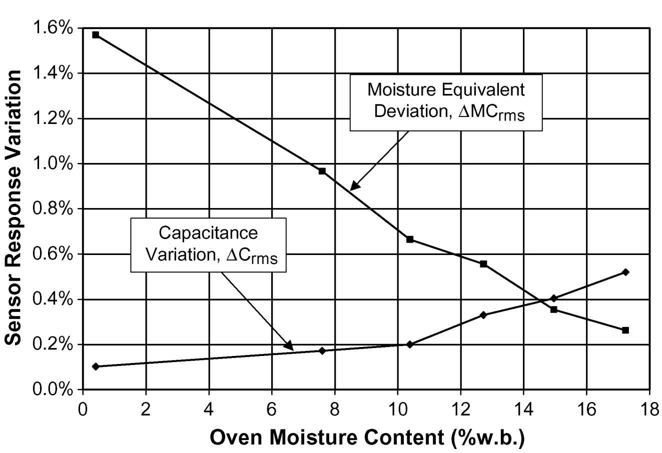


Fig. 12. Capacitance variation and moisture equivalent deviation of a sensing probe inserted into six samples of wheat.

in Fig. 11. For comparison, capacitance data is also plotted for measurements made with a sensor mounted in a canister. The canister data points are mean capacitance values obtained from six hopper fillings.

Fig. 11 allows capacitance variations to be observed between consecutive probe insertions in wheat. There does not appear to be a significant increase in capacitance due to grain compaction with multiple probe insertions. The measurement variations appear to be well behaved which suggests the variability can be described by Gaussian statistics. From the limited measurements obtained with loose wheat in a canister, the capacitance variations appear to be similar to those obtained with a probe in tamped wheat.

TABLE I
SUMMARY OF 25 CONSECUTIVE MEASUREMENTS MADE WITH A PROBE-MOUNTED SENSOR IN WHEAT

| HRW Wheat MC% | Mean Cap. (pF) | Capacitance Variation ($\Delta C_{rms}$) | Capacitance Sensitivity ($\Delta C/MC$) | Moisture Equiv. Dev. ($\Delta MC_{rms}$) |
|---|---|---|---|---|
| 0.4 | 21.98 | 0.10% | 0.065 | 1.54% |
| 7.6 | 23.12 | 0.17% | 0.178 | 0.96% |
| 10.4 | 23.71 | 0.20% | 0.302 | 0.67% |
| 12.7 | 24.80 | 0.33% | 0.593 | 0.56% |
| 15 | 26.61 | 0.40% | 1.14 | 0.35% |
| 17.2 | 30.15 | 0.52% | 1.98 | 0.26% |

The mean and standard deviation $(\Delta C_{\rm rms})$ of the 25 MC data points for wheat obtained with a probe in tamped wheat are given in Table I. The table also includes values of the sensor's capacitance sensitivity to moisture $(\Delta C/MC)$ in units of pF/MC. Values for $\Delta C/MC$ were obtained from the local slope of the curves of Fig. 10 at the corresponding MC values of the wheat using a fourth-order curve fitting equation. Corresponding values were obtained for a term defined as moisture equivalent deviation (MED). MED values $(\Delta MC_{\rm rms})$ were calculated by dividing the capacitance variation $(\Delta C_{\rm rms})$ by $\Delta C/MC$.

Fig. 10 and Table I show that $\Delta C/MC$ increases with increasing MC. At low values of MC, substantially all water molecules have strong physical bonds to dry kernels of grain. The dielectric influence of water vapor in the interstices between kernels is negligible. However, as the MC of grain increases, lower energy bonds form as fewer higher surface energy sites exist. After a first layer of water molecules is adsorbed on a kernel's pericarp, a second layer is attached by weaker hydrogen bonds. This increases the polarizability of the medium because molecules with weaker bonds have more freedom to orientate in an electric field [13], [18]. As a result, $\Delta C_{\rm rms}$ increases at higher values of MC because of the larger effective dielectric constant of the grain, air, moisture matrix. By contrast, MED decreases at higher values of MC since $\Delta C/MC$ decreases at a faster rate than the increase in $\Delta C_{\rm rms}$.

The values of capacitance sensitivity to moisture $(\Delta C/MC)$ in Table I can be used to estimate MC errors due electronics errors and uncertainties in converting output frequency to capacitance. For example, for 12.7% MC wheat, the 25 ppm rms frequency variation of the oscillator corresponds to an equivalent moisture deviation of 0.14% MC. The MED for the 0.0121 kHz uncertainty of (1) is 0.043% MC.

A sensing probe was also used to measure sensor capacitance versus MC of yellow dent corn. This representative response is compared with that of HRW wheat in Fig. 13. Larger push-in forces were required to insert the probe into corn at MC levels

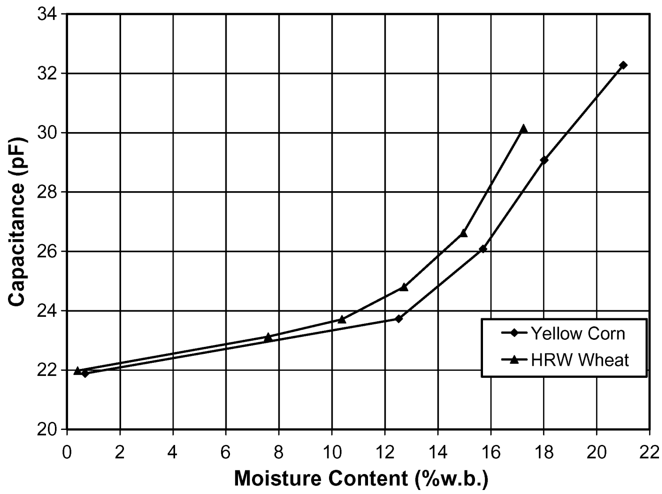


Fig. 13. Capacitance versus MC of wheat and corn measured with a probe.

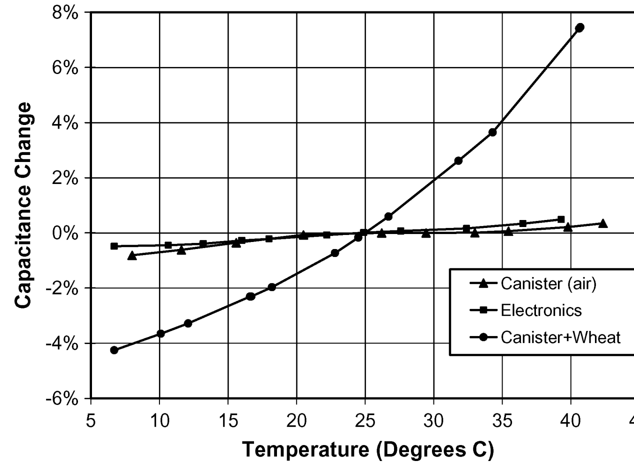


Fig. 15. The thermal response of a sensor in air and in 12.9% MC wheat compared with the response of the capacitance measurement electronics.

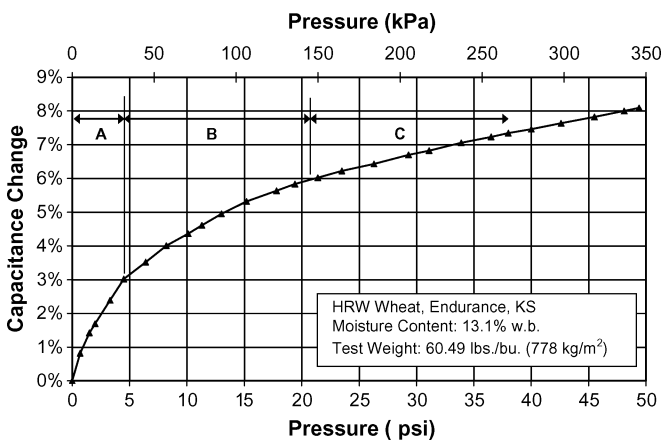


Fig. 14. Plot of capacitance change of wheat versus simulated overburden pressure showing three general regions of grain compaction.

above 16%, a potential source of error, but not one that effects canister or cable-borne measurements.

### *B. Grain Compaction*

The capacitance change of the FFC sensor (Fig. 9) as a function of simulated overburden pressure was measured using the pressure tank shown in Fig. 8. Fig. 14 shows the response of the sensor when pressure is applied to 13.1% MC wheat.

An 8.1% capacitance change was recorded at a pressure of 49.4 psi (34.73 g/m$^2$). This value is reasonable for grain at the bottom and center of a 120 ft (36.6 m) column in a large diameter bin [20]. Since sensor capacitance is dependent upon the effective dielectric constant of the grain, air, and moisture matrix, Fig. 14 indicates the degree to which it is compacted.

The phenomenologies for changes in the bulk density of grain with pressure are generally identified by three regions in Fig. 14. In Region A, compaction at low pressure is believed to be primarily a result of a reduction in intergranular air due to kernel reorientation. In region B, the majority of the kernels are assumed to be immobilized due to friction between kernels. As the area of kernel contact increases with stress, the rate of compaction decreases with pressure. At high pressure, changes in compaction (Region C) appear to become linear due to kernel compression by intergranular stresses [21].

Although the FFC sensor does not directly measure compaction (volume change with pressure) it does provide a means to measure the dielectric constant of grain as a function of pressure for different grain types over a range of MCs.

Similar curves for compaction were determined for soft winter wheat by Thompson and Ross [22]. Uniaxial compression was measured in a shallow, square apparatus with a rubber diaphragm. Compression of the wheat was determined using a dial gauge to measure diaphragm displacement.

### *C. Temperature Response*

Measurements were made to characterize the temperature sensitivity $\Delta C/\Delta T$ of an FFC sensor and its electronics. Three sensors were measured together in an insulated temperature chamber. One sensor was mounted in an empty canister filled with air and a second mounted in a canister filled with 12.9% MC, HRW wheat. The electronics of a third sensor, suspended in air, was connected to an 18 pF, COG ceramic capacitor. Fig. 15 shows plots of capacitance change versus temperature normalized to capacitance values at 25 °C.

In air, the sensor response has a small positive temperature coefficient. Over a 10 °C–40 °C temperature range, the capacitance of a sensor in air increased 0.88%. This compares to an 11% increase for a sensor in a canister filled with HRW wheat with a MC of 12.9%. This indicates that temperature compensation is required to obtain accurate values of MC. This can be accomplished by measuring the temperature of the grain and then referring to a grain specific temperature calibration curve, similar to the (Canister+Wheat) curve in Fig. 15. This method is used by commercial grain moisture meters.

### *D. Dielectric Liquids*

Measurements were made of dielectric fluids and mixtures of alcohol and water to evaluate an easily, reliable method to

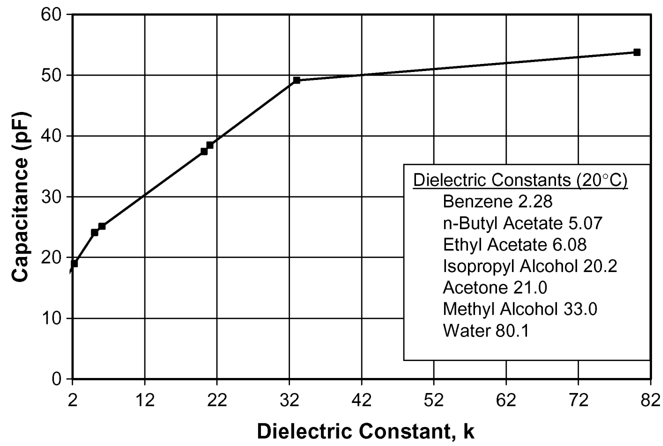


Fig. 16. Capacitance of a sensor immersed in dielectric fluids.

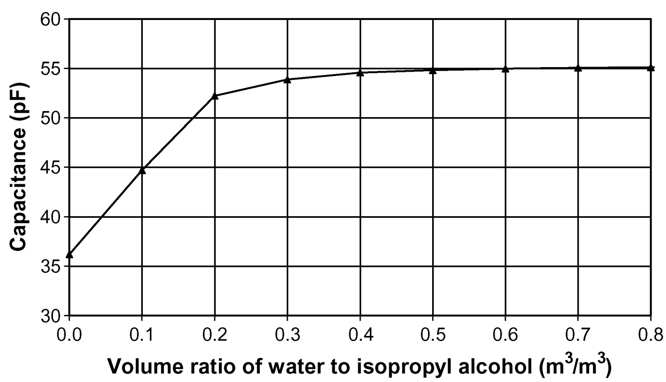


Fig. 17. Capacitance response of a sensor obtained by mixing increasing volumes of DI water with isopropyl alcohol.

calibrate FFC sensors. Fig. 16 is a plot of sensor capacitance for seven dielectric fluids. Fig. 17 is the response for isopropyl alcohol mixed with increasing volumes of deionized water.

Figs. 16 and 17 show the capacitance of a sensor approaches a level of saturation at high values of permittivity. The response in Fig. 17 suggests that the effective dielectric constant for distributed water is lower than bulk water. Alcohol molecules disrupt the hydrogen bonds between water molecules which gives rise to the complex structure of water and its high permittivity compared with other common fluids.

## VI. Cable-Borne Sensors

The representative MC data obtained with FFC sensors mounted on probes and in canisters demonstrate the potential benefits of suspending moisture sensors on cables in grain storage structures. The ability to measure changes in MC and temperature with time, weather, and aeration conditions can provide valuable data for grain storage management. Monitoring the propagation of temperature and drying wavefronts in grain could supply data to enhance the effectiveness of different ambient and chilled aeration control strategies.

Three measurement methods can potentially be used to monitor the MC of stored grain. The first is simply to measure the relative change in apparent MC without compensating a sensor's response for increases in bulk density resulting from the pressure of overbearing grain. The second method involves measuring changes in MC referenced to the MC of the grain at the time of storage. At grain storage facilities, the MC is measured for samples taken from each load of grain as received, before it is placed in storage. This provides significant knowledge of the initial MC of the grain and its distribution in a silo or bin between measurement sites.

It also may be possible to compensate the moisture response of cable-borne sensors by calculating values for the bulk density $\rho$ of gain due to overbearing pressure. Jannsen's equation [19], [20] has been used since 1895 to estimate the vertical pressure $P(z)$ and lateral pressure $P(r)$ that act on the floors and walls of cylindrical silos due to overbearing grain

$$P(z) = \frac{\rho g D}{4\mu k}\left[1 - e^{\frac{-4\mu k z}{D}}\right] \tag{2}$$

$$P(r) = kP(z) \tag{3}$$

where $D$ is the diameter of the silo, $g$ is the acceleration of gravity, $\mu$ the coefficient of friction of silo or bin walls, and $k$ is a ratio of lateral to vertical pressure. The variables $z$ and $r$ are depth and radius from a center line, respectively.

From (2), it can be seen that $P(z)$ asymptotically approaches a consolidation value at a depth where additional increases in pressure are transferred to the walls due to the product of the parameters $\mu$ and $k$. A limitation of (3) is that it's a solution in which $\rho$, $\mu$, and $k$ are constants. In reality, the three material parameters are interrelated variables and functions of pressure, MC, and grain type. Tables of the material properties of grain have been compiled based upon a variety of analytical models and sources of uniaxial compression data [21]–[23]. These data allow more reliable engineering estimates to be made of loads acting on silos and storage bins.

## VII. Conclusion

Representative measurements of wheat and corn indicate that the FFC sensor offers a new and promising capability to measure the MC, temperature, and compaction of bulk stored grain. Sensor performance was characterized by mounting the devices on handheld probes and in 1.5 liter canisters.

The sensor's capacitance sensitivity to changes in the MC of grain was found to be 6–8 times higher than sensors constructed with interdigitated electrodes. This higher sensitivity is attributed to the sensor's larger electrodes and deeper electric field penetration into the measurement media.

For 12.7% MC wheat, the electronic noise floor of the sensor corresponds to an equivalent moisture standard deviation of 0.14% MC. For MC values between 0.4% and 15%, the dielectric constant of settled kernels of HRW wheat measured with a probe was 1.1% higher than that of loose kernels freely dropped by a loading hopper. This demonstrated the feasibility of using FFC sensing probes to make practical estimates of the MC of grain temporarily stored in hoppers at loading sites, and transported in trucks and barges.

The sensor construction allows it to be suspended on cables in grain silos and storage bins. Cable-borne sensors have the potential to provide *in situ* MC and temperature data for grain storage management to help prevent economic losses from insects and fungal growth.

The simple construction of the FFC sensor and its easy calibration in dielectric fluids offers a potential low-cost means at farm sites to provide data to monitor and control the MC and temperature of locally stored grain. Other applications exist for the FFC sensor because of its ability to withstand high pressure, to be immersed in corrosive liquids, and buried in soil.

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