WHEAT MOISTURE MEASUREMENT WITH A FRINGING FIELD CAPACITIVE SENSOR

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ABSTRACT. *Grain storage managers could improve the quality of stored grain if they could directly monitor stored grain moisture content, which is a key indicator of stored grain quality and an early indicator of deterioration. However, shortcomings of currently available sensors have prevented them from achieving widespread acceptance in the industry. A new fringing field capacitive (FFC) sensor was tested to determine its suitability and accuracy for moisture content measurements in grain. Sensors were calibrated at temperature from 10°C to 30°C using six samples of hard red winter (HRW) wheat from three locations and two crop years. The polynomial calibration models had standard error of prediction (SEP) values that averaged 0.68% wet basis (w.b.) moisture content for data not corrected for bulk density. The average SEP improved to 0.50% w.b. when the readings were corrected based on sample bulk density, yielding a 95% confidence interval of ±1.0% w.b. for these data. The measured sensor accuracy, close to that of laboratory instruments, is appropriate for an in situ instrument for monitoring stored grain and for rapid determination of grain moisture content in bulk containers.*

Keywords. *Capacitive sensor, Grain storage, Moisture content, Moisture sensor.*

After many years of research on methods to improve grain storage management and enhance quality grain storage, economic losses of 5% to 10% in stored grain have still been reported in typical U.S. climates (Halderson, 1985; Harein and Meronuck, 1995). When storage environments are not properly maintained, quality and economic losses can occur from such causes as mold growth and insect damage, which are usually the two most troublesome problems to control in modern grain storage structures. Appropriately low grain moisture contents and low grain temperatures are the primary weapons for preventing mold and insect problems.

Monitoring grain temperature is standard practice in many commercial grain storages but is often neglected in on-farm storage. Monitoring grain moisture content, or interstitial relative humidity, has usually been limited to research studies. Ileleji et al. (2006) found that developing hot spots in stored grain easily go undetected by nearby temperature sensors, indicating that temperature sensors alone may not be effective for identifying localized grain deterioration in a larger grain bulk. Moisture content of grain in storage bins has traditionally been determined from grain samples taken from bins.

Most efforts to monitor stored grain moisture have been based on temperature and humidity sensors in research studies. Bunn et al. (1990) investigated the applicability of commercially available humidity sensors based on a hygroscopic capacitor-type transducer. They studied the short-term response characteristics of several commercial sensors, evaluating them for monitoring moisture content when buried in grain. Similar techniques were used by Chung and Verma (1988) to predict the moisture content of rice during drying and storage and by Casada et al. (1992) to predict the moisture content of stored wheat.

Accuracy of the hygoscopic sensors was reduced in a polluted environment (with dust and ammonia) (Erdebil and Leonard, 1989). Visscher and Schurer (1985) reported drift over a three-month test period. Uddin et al. (2006) studied such sensors extensively in laboratory containers and found that errors in predicted moisture contents from sensing errors were comparable to those from using the standard equilibrium equations for predicting moisture content from temperature and humidity measurements. There is little current use of moisture monitoring in storage bins.

McIntosh and Casada (2008) recently described a fringing field capacitive (FFC) transducer that determines the dielectric properties of surrounding media. This sensor responds directly to grain moisture content, rather than measuring equilibrium relative humidity, and is largely immune to contamination and hysteretic problems. When calibrated in agricultural and industrial commodities of known moisture contents, the sensor can be used to measure the moisture content of the commodities (grains, particulates, liquid chemicals, and fuels) as a function of temperature. The simple construction with only the two main electrodes exposed prevents harsh environments from adversely affecting its reliability.

Submitted for review in September 2008 as manuscript number IET 7703; approved for publication by the Information & Electrical Technologies Division of ASABE in July 2009. Presented at the 2008 ASABE Annual Meeting as Paper No. 085207.

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Objectives

The objective of this research was to evaluate the characteristics and accuracy (compared to the air-oven) of the new FFC sensor for measuring wheat moisture content. The accuracy was investigated with sample density variation minimized and also with density manipulated to introduce variation.

Methods

The electrode arrangement and construction of the transducer described by McIntosh and Casada (2008) is shown in figure 1. Two grounded, end-cap electrodes are located at the ends of an actively driven cylindrical electrode (1.9 cm dia. by 4.4 cm long). A PTFE fluoropolymer sleeve electrically insulates the electrodes and provides a chemically resistant and low moisture adsorbing cover that avoids surface contamination.

Electronics inside the sensor measure the transducer capacitance, which varies with the dielectric constant of the surrounding medium. The moisture content of grain can be determined from its dielectric constant, which is primarily determined by the high dielectric constant of water. This use of the dielectric constant of the grain is fundamentally the same approach used by many commercial moisture meters (Nelson, 1977).

The large capacitance values of this FFC sensor allowed a simple, low-cost RC (resistance-capacitance) relaxation oscillator circuit to be used to provide an output frequency related to moisture. The capacitor (the electrodes plus the dielectric medium, the grain) is repeatedly charged and discharged at the frequency of oscillation of the circuit. The time to charge the capacitor varies with the capacitance of the medium and, thus, the output frequency is proportional to the amount of capacitance, which varies with grain moisture content. Frequency output in yellow corn ranged from 51.5 kHz at 12.5% moisture content to 44.4 kHz at 17.2% moisture content. A second output frequency related to temperature is obtained from a surface-mount thermistor chip on the electronics board. Further details of the sensor design and operation are given by McIntosh and Casada (2008).

Although the transducer was designed as a capacitive device, previous studies (e.g., Nelson and Stetson, 1976) have indicated that at the transducer's low operating frequencies, conductivity effects may influence the measurements. These conductivity effects, i.e., electrode polarization and Maxwell-Wagner effects, which may be due to percolating protonic conductivity (Funk, 2001), have been observed at low frequencies and, in wheat, are especially pronounced at moisture contents above about 12% wet basis (w.b.) moisture content. Current research with the FFC sensor has focused on evaluating the accuracy of moisture measurements and density effects, but the contribution of conductivity effects to these moisture readings has not been investigated.

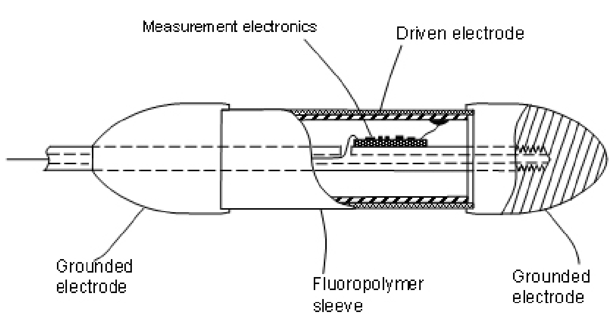

Figure 1. Schematic diagram of moisture sensor.

Two sensor mounting configurations (fig. 2) were investigated. Most testing was with the canister configuration, which provided a consistent method of compacting samples during calibration tests. The canister was comparable to a laboratory instrument for measuring the moisture content of small samples or a stored grain environment with known, controlled grain bulk density. The probe configuration was designed for probing bulk grain at depths up to 0.6 m, an application that, due to vibrating and compacting conditions during transport and handling, would be subject to wider density variation than in the consistently loaded canister tests. Other canister tests were run with samples compacted in the canister to simulate some of the density variation that might occur in the other applications, such as monitoring grain storage bins.

Evaluation of Sensor Performance

The prototype sensor in the canister configuration was calibrated in a temperature-controlled chamber using samples of HRW wheat at five moisture contents and three temperatures (table 1). Six samples of HRW wheat were obtained from three HRW wheat states (Kansas, Oklahoma, and South Dakota). This sample set was constructed to demonstrate the accuracy (based on standard errors of regression) that could be obtained with the FCC sensor for a calibration over multiple crop years, multiple cultivars, and multiple growing locations. Moisture content of the samples was determined by a standard air-oven method (*ASAE Standards*, 2003). Samples for moisture determination were taken from the storage containers using a small grain trier.

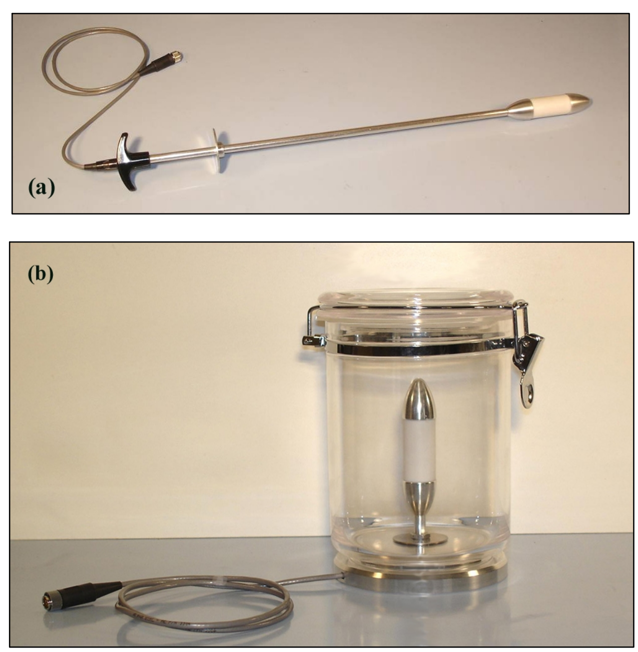

Figure 2. Two moisture sensor test configurations: (a) grain moisture sensing probe and (b) moisture sensor mounted in canister.

Table 1. Experimental conditions for calibration moisture content measurements.

Variable	*N*	Levels
Grain type	1	HRW wheat
Variety/location/year combination	6	Three varieties from three states over two years (see table 2)
Temperature	3	10°C, 20°C, and 30°C
Moisture content	5	Wheat: approximately 8%, 10.5%, 13%, 15.5%, and 18%

Duplicate moisture measurements were taken prior to canister and probe measurements on the pre-conditioned moisture subsamples and again after tests were completed. These four air-oven moisture values were averaged to assign a value to each moisture subsample.

Approximately 50 kg of grain were obtained for each sample set to provide sufficient test material. Subsamples were prepared at five moisture levels (table 1) using wheat initially at 12% to 14% w.b. moisture content (table 2). Higher moisture levels were obtained by tempering in steps of 2.5 percentage points or less; lower moisture levels were obtained by drying at 35°C in a thin layer. Prepared samples were allowed to equilibrate for a minimum of 14 days and were stored in a refrigerator at 5°C until being moved to the test chamber for measurements.

The five moisture subsamples from one sample were moved from refrigeration to a chamber controlled at the lowest test temperature (10°C) and allowed to equilibrate for at least 20 h. A mercury thermometer was inserted in each subsample and the temperature was recorded. Portions of approximately 1.75 L each were withdrawn from each moisture subsample, placed in the canister following the protocol described below, and the sensor readings were recorded. The chamber temperature was raised, and the five subsamples were tested again at 20°C and then at 30°C after equilibrating for at least 20 h each time. The five subsamples from the next sample were then moved into the test chamber, and the process was repeated for the remaining five samples. The mean absolute value of the deviation from the nominal temperature settings was 0.3°C. Measured sample temperatures were used in the models.

Canister Measurement Protocol

Each 1.75 L portion was withdrawn from a container with one moisture subsample, and approximately two-thirds of the portion was loaded into a hopper above a one-quart test weight kettle (Seedburo Equipment Co., Chicago, Ill.). The test weight per bushel (hereafter referred to as test weight) was measured following the USDA-GIPSA (2004) official method, except for using the original sample rather than a sample with dockage removed. However, since the dockage levels in all samples except sample 5 were very low (table 1), five of the six measurements were considered dockage free. Next, this test weight fraction was recombined with the rest of the 1.75 L portion, which was then placed in the hopper and centered over the canister. The valve was opened at the bottom of the hopper, allowing the wheat to pour into the canister. The wheat was leveled and the frequency output of the sensor was recorded, giving a reading hereafter referred to as the loose-fill data. The total number of loose-fill measurements with the canister was 450, comprised of five replicates for each variety, moisture level, and temperature.

Table 2. Characteristics of samples used for calibration tests.

HRW Wheat Sample (state-variety-crop year)	Grade	Initial Moisture Content (% w.b.)	Test Weight, kg hL^{-1} (lb bu^{-1})	Dockage (%)
1. KS-Endurance-2006	U.S. No. 2	12.9	78.0 (59.3)	0.0
2. KS-Endurance-2005	U.S. No. 1	13.5	81.6 (62.0)	0.0
3. OK- 2174-2006	U.S. No. 1	12.4	80.1 (60.9)	0.0
4. OK- 2174-2005	U.S. No. 1	12.8	81.9 (62.3)	0.0
5. SD-Briggs-2006	U.S. No. 1	13.9	79.0 (60.1)	2.6
6. SD-Briggs-2005	U.S. No. 1	14.0	82.5 (62.7)	0.0

After each loose-fill reading, the canister was tapped three times on the side, with a consistent intensity and always by the same operator, with a wooden mallet. These second readings after tapping the canister were called the compacted data. The canister was weighed with a computer grain scale (model 8800A, Seedburo Equipment Co., Chicago, Ill.), and the empty canister mass was subtracted to obtain the grain mass. This canister loading procedure followed the official USDA-GIPSA (2004) test weight measurement protocol except for using the 1.660 L canister instead of an approved kettle and using the original sample as described above. The volume of the canister was determined separately by weighing it empty and again filled with water level with the top of the canister. This mass and density of the water were used to calculate the canister volume, from which bulk density was calculated using the measured grain mass. Measured bulk density from the canister was used to correct the raw frequency readings in a separate analysis that was otherwise similar to the analysis with uncorrected frequency readings. The total number of compacted measurements with the canister was also 450.

Probe Measurement Protocol

Another set of subsamples was prepared from calibration sample 1 (KS-Endurance-2006) at approximately the same five moisture contents (table 1). Each of these subsamples was placed in a 0.2 m diameter PVC cylinder for measurement with the probe. Tests were conducted at 20°C by inserting the probe to a depth of 0.3 m in the grain, removing the probe, and then inserting it again for a total of 25 times for each moisture subsample. The total number of measurements for the probe tests was 125.

Data Analysis

Potential best-fit polynomial models with linear coefficients were evaluated with the GLM procedure of SAS (2002) to determine the maximum number of significant terms ($\alpha = 0.05$). Significant terms were evaluated with the F-statistic based on SAS Type III sums of squares. Significant terms for the model were evaluated with all six sample sets pooled. Using a model with the significant terms determined by the pooled analysis, multiple calibrations were evaluated using a cross-validation analysis. One sample set was left out of each calibration and used as a validation set. Standard errors were calculated as follows (Williams and Norris, 2001):

$$SE_1 = \sqrt{\frac{\sum_{i=1}^{n}\left(M_{i,observed} - M_{i,predicted}\right)^2}{n-c-1}} \quad (1)$$

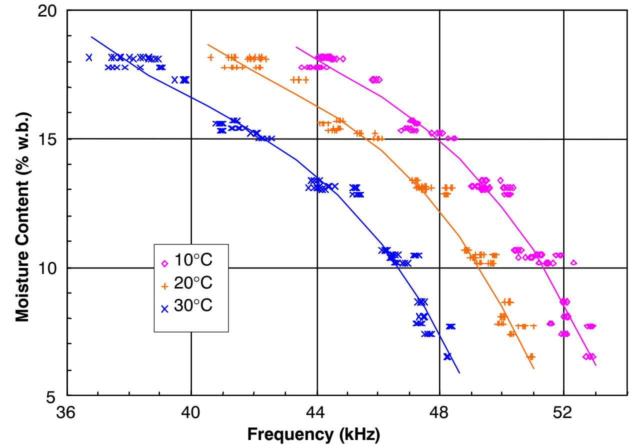

Figure 3. Uncorrected data and best-fit polynomial model for three varieties of HRW wheat at three temperatures.

$$\mathrm{SEC} = \sqrt{\frac{\sum_{i=1}^{m}\left(M_{i,observed} - M_{i,predicted}\right)^2}{m-c-1}} \quad (2)$$

$$\mathrm{SEP} = \sqrt{\frac{\sum_{i=1}^{n}\left(M_{i,observed} - M_{i,predicted}\right)^2}{n-1}} \quad (3)$$

where

SE_1 = standard error of calibration for one individual sample set

SEC = standard error of calibration for a full calibration (primarily for five sample sets combined, with one validation sample left out, but SEC values are also reported for all six sample sets, as noted in the results when determining significant terms for the models)

SEP = standard error of prediction for the sample left out compared to a full calibration from five sample sets

n = number of samples in sample set

m = number of samples for five or six sample sets combined in a full calibration

c = number of coefficients used in the model

$M_{observed}$ = air-oven moisture content for the measured subsample (% w.b.)

$M_{predicted}$ = moisture content predicted by the model (% w.b.).

Table 3. Best-fit polynomial model for uncorrected data.[a]

Coefficient	Term	Estimate	F-Value	p-Value
a	Intercept	972 .2	5.73[b]	<0.0001
b	T	-13 .18	19.0	<0.0001
c	T^2	0 .06185	11.3	0.0009
d	f	0 .5514	22.1	<0.0001
e	f^2	-0 .001514	14.4	0.0002
f	f^3	-0 .005746	25.9	<0.0001
g	T·f	-59 .82	36.3	<0.0001
h	T^2·f	1 .265	42.8	<0.0001
i	T·f^2	-0 .009045	51.8	<0.0001

[a] SEC = 0.572; R^2 = 0.975; model SS = 5705; F = 2123; p < 0.0001.
[b] t-value given for intercept term.

Results and Discussion

Sensor Performance—Loose-Fill Data

Raw loose-fill results (uncorrected results) for five replications of six samples at three temperatures are shown in figure 3. Results from the best-fit polynomial model are plotted for each of the three temperatures. The standard error of calibration (SEC) for the best fit polynomial model from GLM was 0.57% w.b. with all six samples included (table 3).

For the loose-fill data, terms second-order in temperature (T) and third-order in frequency (f) were significant, as were three interaction terms and the intercept (table 3). These same terms were significant in all six calibration runs (table 4) except for one term that was not significant in one calibration. The model was not changed for that isolated case. The results from GLM show that higher-order polynomials did not improve the fit.

For loose-fill samples, the SECs for five samples ranged from 0.54 to 0.60 percent moisture content. The mean SEC for these six sets was 0.57 percent moisture content. The SE_1 values, for each individual sample fit separately with the model, were much lower, averaging 0.24 percent moisture. The variances for the five sample calibrations, corresponding to SEC, averaged 0.32, while the variances for the individual samples, corresponding to SE_1, averaged 0.057, which indicates that there was much more variation between the different samples than within individual samples. Such dominance of variance due to varieties and crop years was also seen with commercial bench-top dielectric moisture instruments (Hurburgh et al., 1987; Funk, 1991) and indicates that these six samples provided the large variation (varieties and crop years) typical of diverse sample sets in the literature.

Sensor Performance—Compacted and Combined Data

Individual SEP values ranged from 0.50 to 0.84 percent moisture content with an overall mean SEP of 0.68 percent moisture content for the combined data set. For the

Table 4. Standard errors (percent moisture content) for uncorrected sample results: M = fct{f, T}.

Calibration	Sample Left Out	Loose-Fill Sensor Readings			Compacted Sensor Readings			Combined Sensor Readings		
		SE_1	SEC	SEP	SE_1	SEC	SEP	SE_1	SEC	SEP
A	6	0.202	0.544	0.788	0.227	0.519	0.761	0.387	0.589	0.800
B	5	0.263	0.547	0.885	0.288	0.521	0.752	0.431	0.587	0.805
C	4	0.215	0.581	0.580	0.190	0.568	0.519	0.334	0.629	0.596
D	3	0.187	0.593	0.545	0.178	0.570	0.520	0.293	0.639	0.549
E	2	0.373	0.595	0.479	0.197	0.589	0.367	0.414	0.643	0.499
F	1	0.198	0.538	0.831	0.241	0.510	0.813	0.365	0.585	0.841
Average		0.240	0.566	0.685	0.220	0.546	0.622	0.371	0.612	0.681

compacted samples, all of the SEC and SEP values were lower than with the loose-fill data. The average SEP was 0.62 percent moisture content, as compared to 0.68 for the loose-fill samples. It is likely that considerable local variation in kernel orientation occurred when the kernels were first poured into the canister and remained in the loose-fill state. When the canister was tapped, the sample kernels had to reorient as they compacted around the sensor in a denser and, presumably, more consistent pattern, resulting in the reduced variation seen for the compacted samples. Not all of the individual SE_1 values were improved with the compacted results, although the average SE_1 was improved compared to the loose-fill values. Perhaps that was because some samples randomly had a more oriented, consistent pattern during the initial canister filling.

When both the loose-fill and compacted data were combined, the SEC values for the calibration were higher than with either data set alone. The larger density variation included with the two different canister loading methods should cause larger variation in the readings, resulting in the observed higher SEC values. However, the SEP values were no larger than those measured with the loose-fill data set only, which had more natural density variation than did the compacted data set.

Combined results with both loose-fill and compacted samples approximate the extremes of variation due to density changes expected for samples that would be probed with the sensor to measure moisture content. Based on the average SEP for the combined data set, the expected accuracy of readings with this sensor used as a probe with uncontrolled density of the samples would be ±1.3% moisture content for a 95% confidence interval. Error from additional compaction occurring if the sensor were used in a deep grain storage bin is expected to exceed this value, but correction factors based on depth and bulk density could probably be implemented to offset the potential error from increased compaction in that situation; these corrections are the subject of ongoing research.

Another set of subsamples at approximately the same five moisture contents from calibration sample 1 (KS-Endurance-2006) were placed in cylinders and measured repeatedly with the probe. The mid-range and high moistures, 13.1% and 18.0% w.b., readings are shown in figure 4. There is a slight trend of increasing apparent moisture content as the number of insertions increased (slope = 0.012% w.b.; R^2 = 0.388) at the mid-range moisture. This increase occurred because inserting the probe in the cylinder caused the grain to compact. The effect was greater at higher moisture contents; at 18.0% w.b. moisture content the slope was 0.053% w.b., with R^2 = 0.717, which is apparently due to increased friction between the probe and grain at higher moisture contents.

The SE_1 for the probe was 0.35 % w.b., which was similar to that for the comparable data from the canister, 0.36 % w.b. (table 4, calibration F = sample 1, combined sensor reading). The SEP for the probe data compared to calibration F was lower than the SEP for the canister results, 0.63 compared to 0.84 for the canister (table 4). This effect of density variation from compaction caused by probing the container was smaller than that produced by combining canister loose-fill and compacted readings. The combined loose-fill and compacted readings may approximate the upper bound on the amount of density variation that would exist at shallow depths, depths comparable to the moisture probe length, in small containers or cargo holds. Field measurements will be required to confirm the amount of variation.

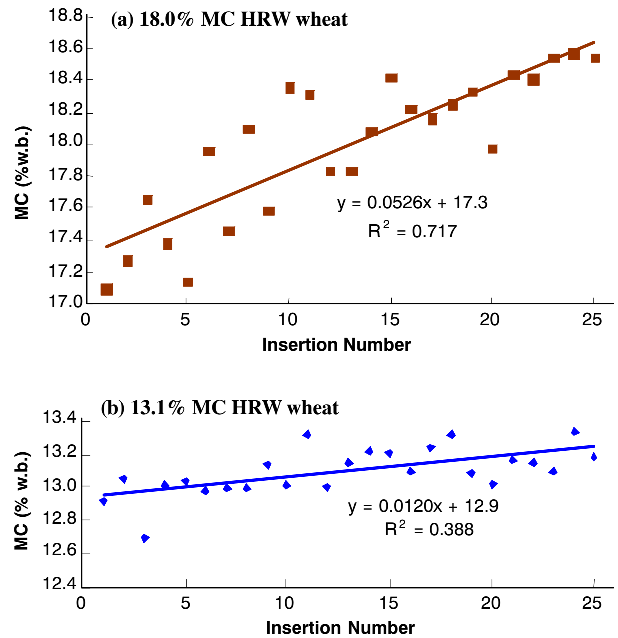

Figure 4. Twenty-five successive readings taken with probe sensor in two wheat samples.

Evaluation of Density Correction

The official test weight measurements from the standard kettle and the bulk density measurements from the canister are compared in figure 5 for the original 450 canister samples. The canister values, calculated directly in kg hL^{-1}, were generally consistent with the values determined in lb bu^{-1} with the standard one-quart kettle and then converted to kg hL^{-1} using the USDA-GIPSA (2004) conversion and adjustment formula. The canister measurements were slightly higher than the official kettle values at the upper end of the observed range. There were a total of 15 replications

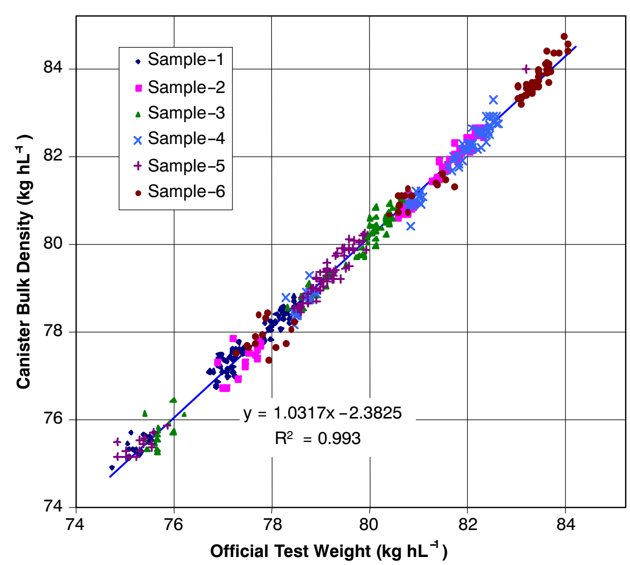

Figure 5. Bulk density measured with canister compared to official test weight.

for each sample at each moisture content (five replications each at three different temperatures). The mean and standard deviation were calculated for each set of 15 replications, and these were averaged for all observations from both the official test weight and the bulk density measurements. The average standard deviation for the canister bulk density means was 0.272 kg hL^{-1}, while for the official kettle the average standard deviation was lower at 0.180 kg hL^{-1}.

With the strong correlation between bulk density measured with the canister and test weight measured with the official kettle, either of these values should be effective to investigate the effect of density on the moisture measurements. If the sensor were being used in this configuration, then the bulk density determined with the canister would be more readily available. Thus, the bulk density determined with the canister was added to the model to correct for sample bulk density, again using GLM to determine the significant terms for determining the moisture content from all three measurements: sensor frequency (f), temperature (T), and bulk density (d). The complete data set with all six HRW wheat samples was again fit to potential models. Significant terms are shown in table 5.

A cross-validation analysis was again run with the resulting 13-term model, leaving out one sample for each calibration, and the results are summarized in table 6. All of these SEC and SEP values were lower than the standard errors when density was not included (table 4). For SEP, the reduction was 22% and 19% for the loose-fill and compacted results, respectively. With bulk density included in the model, there were small differences for the compacted readings compared to results without bulk density; not all SEP values for the compacted readings were lower compared to the loose-fill readings, but the average SEP was lower. In addition, as with the uncorrected data, not all individual SE_1 values were lower for the compacted data compared to the loose-fill data, but the average SE_1 was lower (table 6). Based on the compacted samples, the expected accuracy of readings with this sensor when including a bulk density correction would be ±1.0% moisture content for a 95% confidence interval.

The average SEP of 0.50% moisture for this case is a little higher than the standard error of 0.40% moisture reported for soft red winter (SRW) wheat using carefully selected official instruments and samples for five years from all parts of the U.S. (Funk, 1991). Testing with a larger number of samples would be required to see if the SEP would differ for a set of samples with a smaller moisture range but greater diversity of materials similar to the SRW wheat study.

This accuracy when bulk density is included, which was about 20% better than without the correction, should be indicative of the accuracy that can be achieved when using the sensor in a bench-top configuration where the bulk density is measured simultaneously with the sensor reading. Based on the comparison in figure 5, the test weight measured separately with another (official) apparatus should yield a similar reduction in SEP. Thus, a similar improvement in accuracy, about 20%, may be possible when probing grain if the test weight of the sample is known from separate measurements, such as from grading the grain.

When sensors are buried in grain bins to monitor stored grain, it would be desirable to also use official test weight combined with local bulk density (which varies with depth due to compaction from overburden pressure) to correct the moisture readings. Changes in bulk density due to overburden pressure can be determined with the differential form of Janssen's equation (Janssen, 1895; Ross et al., 1979) using available pressure-density data for bulk grain (Thompson and Ross, 1983; Thompson et al. 1987). The most important application of the sensors for monitoring stored grain would likely be monitoring changes in moisture content during storage. Errors from predicting local density should be constant over time in an undisturbed bin and, thus, should not reduce the accuracy of moisture change measurements in stored grain. Additional research will be required to determine the accuracy that can be obtained using the sensors buried in stored grain to monitor moisture content or moisture content changes.

The accuracy of the new sensor appears to be slightly inferior to the best laboratory instruments; however, the sensor is intended for use in monitoring stored grain and as a probe for quick moisture determinations that do not require extracting samples from the grain bulk. Thus, the major

Table 5. Best-fit polynomial model with bulk density correction.[a]

Coefficient	Term	Estimate	F Value	p-Value
a	Intercept	1298	9.7[b]	<0.0001
b	T	-15.75	37.4	<0.0001
c	T^2	0.09924	44.5	<0.0001
d	f	-86.03	123	<0.0001
e	f^2	1.869	152	<0.0001
f	f^3	-0.01306	175	<0.0001
g	d	2.835	24.4	<0.0001
h	T·f	0.7594	65.8	<0.0001
i	T^2·f	-0.002335	53.2	<0.0001
j	T·f^2	-0.008934	98.5	<0.0001
k	T·d	-0.08711	12.0	0.0006
l	f·d	-0.06411	30.1	<0.0001
m	T·d·f	0.001823	12.0	0.0006

[a] SEC = 0.424; R^2 = 0.986; model SS = 5773; F = 2605; $p < 0.0001$.
[b] t-value given for intercept term.

Table 6. Standard errors (percent moisture content) for samples corrected with bulk density: M = fct{f, T, d}.

Calibration	Variety Left Out	Loose-Fill Sensor Readings			Compacted Sensor Readings		
		SE_1	SEC	SEP	SE_1	SEC	SEP
A	6	0.181	0.417	0.552	0.188	0.403	0.503
B	5	0.179	0.404	0.548	0.204	0.377	0.605
C	4	0.167	0.441	0.371	0.148	0.426	0.334
D	3	0.116	0.398	0.622	0.120	0.380	0.576
E	2	0.295	0.414	0.532	0.111	0.425	0.366
F	1	0.191	0.415	0.596	0.220	0.384	0.636
Average:		0.188	0.415	0.537	0.165	0.399	0.503

advantages of this new sensor are that it is an *in situ* device and that it is much simpler than the laboratory meters. The second advantage should lead to lower cost than typical laboratory meters, which generally cost at least $1000 (U.S.) and cost several thousand dollars (U.S.) for certified instruments. The parts for the FCC sensor cost only a few dollars (U.S.).

Conclusion

The following conclusions were formulated based on the results of this study:

The new sensor demonstrated an accuracy of ±1.0% moisture content (95% CI) compared to the air-oven when used in a laboratory setting where sample bulk density was measured and included in the calibration. The accuracy (from SEP = 0.50% w.b.) compares reasonably well with that of the best laboratory capacitive moisture meters (SEP = 0.40% w.b.). This accuracy seems suitable for monitoring stored grain or rapidly determining moisture content in bulk grain.

The sensor accuracy was reduced to ±1.3% moisture content when calibrated directly from sensor capacitance and temperature readings and including uncorrected variation in the calibration data from using a combination of loose-fill and compacted samples.

Housing the sensor in a canister made it possible to obtain simultaneous bulk density measurements well-correlated with that obtained with the official test weight determination method, resulting in the accuracy improvement, noted above, from ±1.3% moisture content without bulk density to ±1.0% moisture content with bulk density.

Acknowledgements

We thank Stephen Delwiche (USDA-ARS BARC) and Paul Flinn (USDA-ARS GMPRC) for reviewing an early version of the manuscript. Special thanks to Dennis Tilley (USDA-ARS GMPRC) for technical assistance with the measurements and data analysis, and to Robert McIntosh (Horizon Technology, Inc.) for supplying the sensors and advice for the tests.

References

ASAE Standards. 2003. S352.2: Moisture measurement - Unground grain and seeds. St. Joseph, Mich.: ASAE.

Bunn, J. M., M. J. Buschermohle, and R. A. Spray. 1990. Measuring relative humidity in a stagnant environment. *Applied Eng. in Agric.* 6(1): 101-105.

Casada, M. E., D. Pietersma, A. Alghannam, J. L. Halderson, and J. B. Johnson. 1992. Performance of an in-bin moisture sensor. ASAE Paper No. 926506. St. Joseph, Mich.: ASAE.

Chung, J. H., and L. R. Verma. 1988. Dynamic and quasi-static rice moisture models using humidity sensors. ASAE Paper No. 886585. St. Joseph, Mich.: ASAE.

Erdebil, I., and J. Leonard. 1989. Performance of humidity sensors in a simulated animal environment. ASAE Paper No. PNR 89401. St. Joseph, Mich.: ASAE.

Funk, D. B. 1991. Uniformity in dielectric grain moisture measurement. In *Uniformity by 2000*, 69-91. L. D. Hill, ed. Urbana, Ill.: University of Illinois.

Funk, D. B. 2001. An investigation of the nature of the radio-frequency dielectric response in cereal grains and oilseeds with engineering implications for grain moisture meters. PhD diss. Kansas City, Mo.: University of Missouri, Department of Physics.

Halderson, J. L. 1985. Results of a grain storage study in Idaho. *Trans. ASAE* 28(1): 246-250.

Harein, P., and R. Meronuck. 1995. Stored grain losses due to insects and molds and the importance of proper grain management. In *Stored Product Management*, 29-31. E-912. Stillwater, Okla.: Oklahoma State University, Cooperative Extension Service.

Hurburgh, C. R., Jr., L. N. Paynter, and S. G. Schmitt. 1987. Moisture meter performance: I. Corn over five crop years. *Trans ASAE* 30(2): 579-581.

Ileleji, K. E., D. E. Maier, C. Bhat, and C. P. Woloshuk. 2006. Detection of a developing hot spot in stored corn with a CO_2 sensor. *Applied Eng. in Agric.* 22(2): 275-289.

Janssen, H. A. 1895. Versuche uber getreidedruck in silozellen. *Zeitschrift, Verein Deutscher Ingenieure* 39: 1045-1049.

McIntosh, R. B., and M. E. Casada. 2008. Fringing field capacitance sensor for measuring the moisture content of agricultural commodities. *IEEE Sensors* 8(3): 240-247.

Nelson, S. O. 1977 Use of electrical properties for grain moisture measurement. *J. Microwave Power* 12(1): 67-72.

Nelson, S. O., and L. E. Stetson. 1976. Frequency and moisture dependence of the dielectric properties of hard red winter wheat. *J. Agric. Eng. Res.* 21(2): 181-192.

Ross, I. J., T. C. Bridges, O. J. Loewer, and J. N. Walker. 1979. Grain bin loads as affected by grain moisture content and vertical pressure. *Trans. ASAE* 22(3): 592-597.

SAS. 2002. The SAS system for Windows, release 8.0. Cary, N.C.: SAS Institute, Inc.

Thompson, S. A., and I. J. Ross. 1983. Compressibility and frictional properties coefficients of wheat. *Trans. ASAE* 26(4): 1171-1176, 1180.

Thompson, S. A., S. G. McNeill, I. J. Ross, and T. C. Bridges. 1987. Packing factors of whole grains in storage structures. *Applied Eng. in Agric.* 3(2): 215-221.

Uddin, M. S., P. R. Armstrong, and N. Zhang. 2006. Accuracy of grain moisture content prediction using temperature and relative humidity sensors. *Applied Eng. in Agric.* 22(2): 267-273.

USDA-GIPSA. 2004. Chapter 1: General information. Book II: Grain grading procedures. In *Grain Inspection Handbook.* Washington, D.C.: USDA Grain Inspection, Packers, and Stockyards Administration, Federal Grain Inspection Service.

Visscher, G. J. W., and K. Schurer. 1985. Some research on the stability of several capacitive thin film (polymer) humidity sensors in practice. In *Proc. 1985 Intl. Symposium on Moisture and Humidity*, 515-523. Washington, D.C.: Instrument Society of America.

Williams, P. C., and K. H. Norris. 2001. *Near Infrared Technology in the Agriculture and Food Industries.* 2nd ed. St. Paul Minn.: American Association of Cereal Chemists.