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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, currently available sensors are too expensive and lack the necessary reliability in that harsh environment. A new fringing field capacitive (FFC) sensor was tested to determine its suitability and accuracy for moisture content measurements in grain. Sensors were calibrated using six samples of hard red winter (HRW) wheat from three locations and two crop years over a temperature range of 10° to 30°C. The linear 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 ±0.99% 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. Moisture content, grain storage, moisture sensor, capacitive sensor

Introduction

After many years of research on methods to improve grain storage management and enhance quality grain storage, 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 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 sensors of this type was found to be reduced in a polluted environment (with dust and ammonia) by Erdebil and Leonard (1989). Visscher and Schurer (1985) reported that this type of sensor drifted 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 the errors 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 because currently available commercial moisture sensors are too expensive and do not last more than one year.

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. The electrode arrangement and construction of the transducer is shown in fig. 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 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 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).

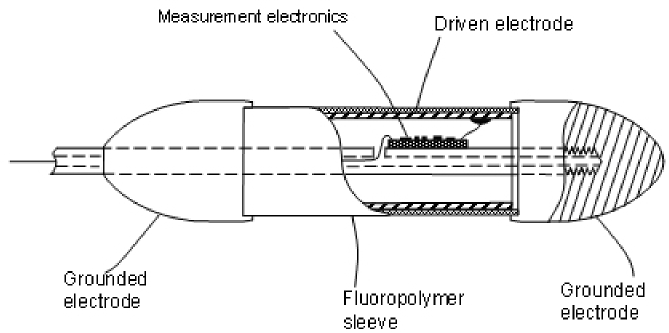


Figure 1. Schemetic diagram of moisture sensor.

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, electrode polarization and Maxwell-Wagner effects, which may be due to percolating protonic conductivity (Funk, 2001), have been observed at these low frequencies and are especially pronounced at moisture contents above about 12% wet basis (w.b.) moisture content in wheat. Current research with the FFC sensor has focused on evaluating the accuracy of moisture measurements, but the contribution of conductivity effects to these moisture readings has not been investigated.

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.

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. The varying density facilitated assessing the potential of the sensor for monitoring stored grain moisture content.

Methods

Two sensor mounting configurations, shown in fig.2, were investigated. Most testing was with the canister configuration, which provided a consistent method of compacting samples during calibration tests. The canister simulated 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 occurs in the consistently-loaded canister tests. Other canister tests were run with samples compacted in the canister to simulate density variation that would occur in the other applications.

(a) Grain Moisture Sensing Probe

(b) Moisture Sensor Mounted in Canister

Figure 2. Two moisture sensor test configurations.

Evaluation of Sensor Performance

The prototype sensor in a canister 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). Moisture content of the samples was determined by a standard air-oven method (ASAE, 2003). Samples for moisture determination were taken from the storage containers using a small grain trier. Duplicate moisture samples were taken before each set of measurements with individual moisture subsamples and again after each subsample was tested. These four air-oven moisture values were averaged to assign a value to each moisture subsample.

Table 1. Experimental conditions for calibration moisture content measurements.

Variable	N	Levels
Grain Type	1	HRW Wheat
Variety/Location/Year	6	3 varieties from 3 states over 2 years (table 2)
Temperature	3	10°C, 20°C, 30°C
Moisture Content	5	wheat: ca. 8%, 10.5%, 13%, 15.5%, 18%

Approximately 50 kg of grain were obtained for each sample set to provide sufficient 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 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.

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 (lb/bu)	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%

The five moisture subsamples from one sample at a time 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 recorded before testing. Portions of approximately 1.75 L each were withdrawn from each moisture subsample, placed in the canister, and the sensor reading recorded for all five subsamples. The chamber temperature was raised and the five subsamples were tested again at 20°C then at 30°C after equilibrating for at least 20 h each time. The five subsamples from the next sample were moved into the test chamber and the process 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 always 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 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 number 5 were very low (table 1), five of the six measurements were essentially dockage free. Next, this test weight fraction was recombined with the rest of the 1.75 L portion, which was all 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.

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 Seedburo Model 8800A Computer Grain Scale (Seedburo Equipment Co., Chicago, IL) 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 a standard kettle and using the original sample rather than a dockage-free sample. 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 first analysis.

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 measuring 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, then inserting again a total of 25 times for each moisture subsample. The total number of measurements was 125.

Data Analysis

Potential best-fit linear models were evaluated with the GLM procedures of SAS (2002) until the maximum number of significant terms (α = 0.05) were determined. 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. Multiple calibrations were evaluated using a cross-validation type analysis using the aforementioned model determined by the pooled analysis. Appropriate standard errors were calculated as follows:

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

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

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

where,

SE_1 = standard error of calibration for one individual sample set alone,
SEC = standard error of calibration for a full calibration: five sample sets combined, one left out,
SEP = standard error of prediction for the sample left out compared to a full calibration,
n = number of samples in sample set,
m = number of samples for five 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., and
$M_{predicted}$ = moisture content predicted by the model, % w.b.

Results and Discussion

Sensor Performance – Loose-Fill Data

The raw loose-fill results (uncorrected results) for five replications of six samples at three temperatures are shown in fig. 3. Results from the best-fit linear model are plotted for each of the three temperatures. The standard error for the best fit linear model from GLM was 0.619 % w.b. (table 3).

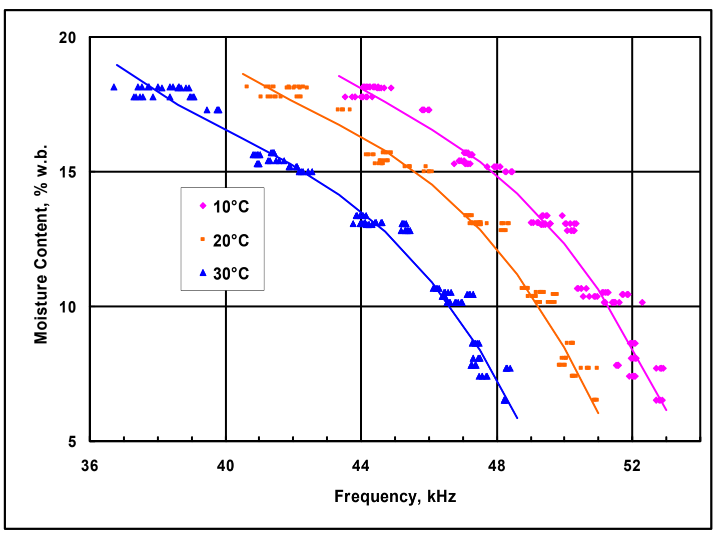


Figure 3. Uncorrected data and best-fit linear model for 3 varieties of HRW wheat at 3 temperatures.

Results from GLM for the loose-fill data showed that terms second-order in temperature and third-order in frequency 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.

Table 3. Best-fit linear model for uncorrected data.

Coefficient	Term	Estimate	F-value[1]	p-value
a	Intercept	972.2457325	5.73	< 0.0001
b	T	-13.1752702	19.04	< 0.0001
c	T^2	0.0618519	11.28	0.0009
d	F	0.5513978	22.08	< 0.0001
e	F^2	-0.0015137	14.43	0.0002
f	F^3	-0.0057457	25.91	< 0.0001
g	$T \cdot F$	-59.8197594	36.34	< 0.0001
h	$T^2 \cdot F$	1.2651147	42.82	< 0.0001
i	$T \cdot F^2$	-0.0090451	51.85	< 0.0001

SEC = 0.572; R^2 = 0.975

Model SS = 5705; F = 2123; $p < 0.0001$

[1] t-value given for intercept term

For the loose-fill samples, the standard errors of calibration (SEC) with five samples ranged from 0.538 to 0.595 percent moisture. The mean SEC for these six sets was 0.566 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 0.321 while the variances for the individual samples, corresponding to SE_1, averaged 0.057, which indicated there was much more variation between the different samples, than there was within individual samples. Such dominance of variance due to varieties and crop years has also been found with standard bench top dielectric moisture instruments (Hurburgh et al., 1987; Funk, 1991).

Table 4. Standard errors 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:	3.5	0.240	0.566	0.685	0.220	0.546	0.622	0.371	0.612	0.681

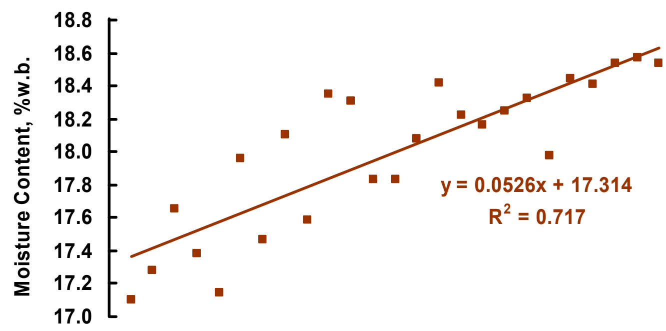
Sensor Performance – Compacted and Combined Data

Individual SEP values ranged from 0.479 to 0.885 percent moisture with an overall mean SEP of 0.681 percent moisture content for this combined data set. For the compacted samples all of the SEC and SEP values were lower than with the loose-fill data. The average SEP was 0.622 percent moisture content as compared to 0.685 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.

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 these two canister loading methods would cause extra variation in the readings leading to higher SEC values. Interestingly, the SEP values were no larger than those measured with the loose-fill data set only.

These results with loose-fill and compacted samples combined approximate the extremes of density variation 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 ± 1.33 % 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 fig. 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 0.063% w.b., with R^2 = 0.717 — apparently due to increased friction between the probe and grain at higher moisture contents.



a. 18.0% moisture content HRW wheat

b. 13.1% moisture content (MC) HRW wheat

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

The SE_1 from GLM for the probe was 0.351, which was similar to that for the comparable data from the canister, which was 0.365 % w.b. (table 4). The SEP for the probe data compared to calibration F was lower than the SEP for the canister results, 0.633 compared to 0.841 for the canister (table 4). This effect of density variation from compaction caused by probing the container was smaller than produced by combining loose-fill and compacted readings in the canister. The combined loose-fill and compacted readings in the canister may approximate the upper-bound on the amount of density variation that would exist at shallow depths, comparable to the moisture probe length, in small containers or cargo holds. Field measurements will be required to confirm the amount of variation.

Evaluation of Density Correction

The official test weight measurements from the standard kettle and the bulk density measurements from the canister are compared in fig. 5 for the original 450 canister samples. The canister values, calculated directly in kg/hL, were generally consistent with the values determined in lb/bu with the standard one-quart kettle and then converted to kg/hL using the USDA-GIPSA (2004) conversion formula. The canister measurements were slightly higher than the official kettle values at the upper end of the observed range. With five replications of the measurements each time there were a total of 15 replications for each sample at each moisture content (five each at three different temperatures). The mean and standard deviation were calculated for each set of 15 replications and these were averaged for all the 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, while for the official kettle means the average standard deviation was lower at 0.180 kg/hL.

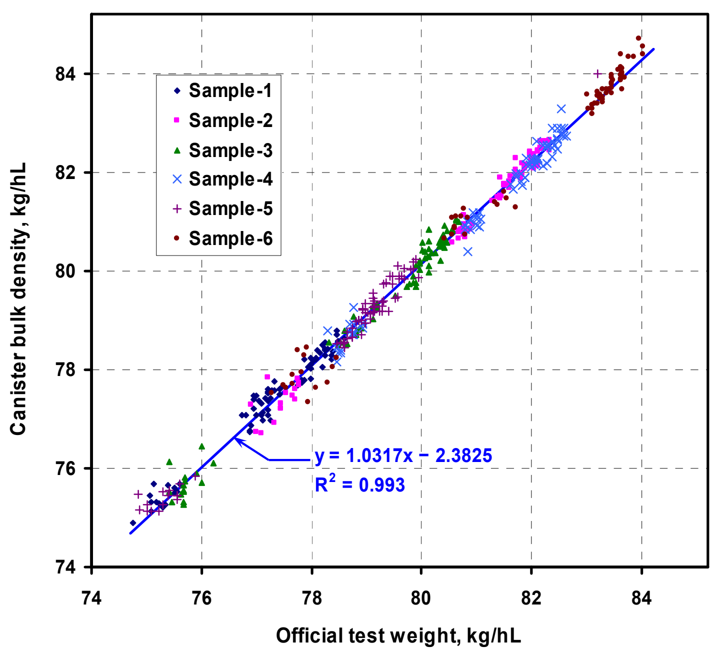


Figure 5. Bulk density measured with canister compared to official test weight.

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 useful to investigate the effect of density on the moisture measurements. If the sensor were being used in this configuration, 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 order of terms that were significant in determining the moisture content from all three measurements: sensor frequency, temperature, and bulk density. The complete data set with all six HRW wheat samples was again fit to potential models. The terms found to be significant are shown in table 5.

Table 5. Best-fit linear model with bulk density correction.

Coefficient	Term	Estimate	F value[1]	p-value
a	Intercept	1297.59030	9.72	< 0.0001
b	T	-15.753169	37.37	< 0.0001
c	T^2	0.099237	44.46	< 0.0001
d	F	-86.032986	122.91	< 0.0001
e	F^2	1.869088	151.52	< 0.0001
f	F^3	-0.013061	175.23	< 0.0001
g	W	2.834938	24.36	< 0.0001
h	$T \cdot F$	0.759357	65.82	< 0.0001
i	$T^2 \cdot F$	-0.002335	53.20	< 0.0001
j	$T \cdot F^2$	-0.008934	98.52	< 0.0001
k	$T \cdot W$	-0.08711	12.05	0.0006
l	$F \cdot W$	-0.064108	30.09	< 0.0001
m	$T \cdot F \cdot W$	0.001823	12.04	0.0006

SEC = 0.424; R^2 = 0.986; Model SS = 5773.; F = 2605.; $p < 0.0001$

[1] t-value given for intercept term

A cross-validation type analysis was again run with the resulting thirteen-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, the improvement for the compacted readings was similar to results without bulk density — all SEP values for the compacted readings were all lower compared to the loose-fill readings. And, as with the uncorrected data, not all individual SE_1 values were lower with the tapped data, but the average SE_1 was lower. Based on the compacted samples the expected accuracy of readings with this sensor when including a bulk density correction would be ± 0.99 % moisture content for a 95% confidence interval.

Table 6. Standard errors for samples corrected with bulk density — M = fct{F, T, TW}.

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

The standard error of 0.503% 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 as in the SRW wheat study.

This accuracy when bulk density is included, which was 19% better than without the correction, should be indicative of the accuracy that can be achieved using the sensor in a bench top configuration where the bulk density is measured simultaneously with the sensor reading. Based on the comparison in fig. 5, the test weight measured separately with another (official) apparatus should yield a similar reduction in SEP. Thus, a similar improvement in accuracy 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 (e.g., 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 lower than the best laboratory instruments; however, the sensor is intended mainly for use monitoring stored grain and also as a probe for quick moisture determinations that don’t require extracting samples from the grain bulk. Thus, the major advantages of this new sensor are that it is (1) an *in situ* device and (2) is much simpler than the laboratory meters; the second advantage should also lead to lower cost than typical laboratory meters. Having accuracy close to that of laboratory instruments at a lower cost are desirable attributes for a stored grain monitoring device.

Conclusion

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

The new sensor demonstrated an accuracy of ± 0.99% 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 ± 1.33% 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 ± 1.33% moisture content without bulk density to ± 0.99% moisture content with bulk density.

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