DENSITY-INDEPENDENT MICROWAVE MEASUREMENT OF MOISTURE CONTENT IN STATIC AND FLOWING GRAIN

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ABSTRACT. Conventional techniques for the determination of moisture content in grain often use small static samples to represent several tons of material. A more desirable alternative would be a method which utilizes continuous dynamic measurement of the grain. The potential for making density-independent moisture content measurements in both static and flowing grain using microwave frequencies was evaluated in tests with soft red winter wheat over moisture contents from 11% to 19% (w.b.). Moisture measurements were predicted within ±0.7% for the static samples and within ±1.2% for wheat in a dynamic solid-flow condition. For suspended flow (aerated sample of grain) scatter became more apparent and the system accuracy decreased. Keywords: Grain, Moisture content, microwaves, NMR.

Correct determination of grain moisture content is critical during all harvest and postharvest operations. Currently, electrical-capacitance-type moisture meters are the most common method for determining moisture content of grain. These devices sense a capacitance change when a static sample of granular material is introduced. This change is caused by the dielectric properties of the material, which vary with both the moisture content and the bulk density of the sample. Conventional techniques for the determination of moisture content often use sample sizes of 250 g or less to represent the average moisture content of several tons of material. For this sampling technique to be statistically accurate, the sample must be representative of the bulk material, the moisture content must be uniform, and multiple samples are needed that are randomly collected. A nondestructive, continuous dynamic measurement of the moisture content of the entire quantity as the grain is moving would be a desirable alternative to the sampling techniques. Current methods being researched for continuous-flow moisture measurement include sound pressure level measurements, nuclear magnetic resonance (NMR), and microwave measurements.

Mexas and Brusewitz (1987) have shown that the sound pressure levels produced by a stream of grain falling onto a grain-filled funnel vary with moisture content. The basic problem lies in maintaining a constant grain flow and a controlled distance between the microphone and the grain sound source.

NMR methods have demonstrated some possibilities for accurate moisture measurements. Brusewitz and Stone (1987) have indicated that, in tests conducted with wheat, NMR produced a response that was independent of the wheat mass, bulk density, and cheat content. Their results were typically within 0.1% of the actual moisture content. However, Christensen (1982) states that the determination of moisture in grain products by NMR has not been widely accepted because the equipment is expensive and the results are also affected by lipid content.

Kraszewski et al. (1977) and Meyer and Schilz (1980, 1981) have indicated that microwave frequencies provide distinct advantages over lower frequencies in the megahertz (MHz) range since measurement in the lower frequency range is more likely to be dependent upon the ionic conduction. At frequencies above 10 GHz, microwave absorption results mainly from dielectric relaxation of water. The purpose of this research was to evaluate the potential for making density-independent moisture content measurements on static and flowing grain using microwave frequencies.

MATERIALS AND METHODS

CIRCUIT DESIGN

A microwave circuit similar to that described by Powell et al. (1988), was used in making all moisture measurements (fig. 1). Significant improvements were made in the modified circuit by replacing the RG-142 flexible cables with rigid coaxial lines and SMA connectors and by using ferrite isolators to minimize the effects of microwave reflections. The theoretical basis for the measurements as described by Powell et al. (1988), depends upon a 90° phase shift between the reference signals provided to the LO input of the mixers. The hybrid splitter provides this needed phase shift. However, since the other components (i.e., connectors, isolators, etc.) introduce both attenuation and phase shift, the microwave phase shift at the mixer LO ports is not exactly 90°. Phase trimmers allowed the needed 90° (±0.5) shift to be obtained. The values for attenuation and phase shift were calculated as follows:

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Horn antennas

Figure 1—Block diagram of the microwave measurement system.

$$\text{Attenuation (dB)} = 20 \log \left( \frac{(E_1^2 + E_2^2)^{1/2}}{(E_{1\text{Ref}}^2 + E_{2\text{Ref}}^2)^{1/2}} \right)$$

(1)

$$\text{Phase (deg)} = \tan^{-1} \left( \frac{E_1}{E_2} \right) \pm k (180^\circ)$$

(2)

$$\text{Phase shift (deg)} = \text{Phase angle}_{\text{sample}} - \text{Phase angle}_{\text{reference}}$$

(3)

where $E_1$ and $E_2$, the mixer outputs, are unit consistent (volts or millivolts), and $k$ is an integer.

Manufacturer’s specifications were found to be inadequate for component selection, since parameters are often dependent upon the frequency. Large variations were found between components even when made by the same manufacturer. Therefore, a Hewlett Packard 8510B Network Analyzer was used to obtain voltage standing wave ratio (VSWR), isolation, and transmission loss data for key components. Component interconnections were judiciously made to provide comparable phase shifts and losses in circuit branches and to provide the appropriate component matching.

Two, double-ridged, die cast, broad-band horn antennas (32 mm x 44 mm aperture, 60 mm long) were chosen which had similar VSWR characteristics. The best impedance matching was obtained at 9.6 GHz. A Gunn-diode oscillator (MA-COM model MA 86683-M08) that provided 170 mW microwave signal at 9.6 GHz ($\pm 25$ MHz mechanical tuning) was then selected to feed the circuit.

The mixers were rated for 10 to 17 dBm at the LO port and transmission losses introduced by interconnecting components (i.e., splitter, connectors, etc.) resulted in a delivered power of about 15 dBm. The mixers, a critical system component, were double balanced thin-film mixers (Avantek TFX-158M). The mixers’ phase imbalance and offset are temperature dependent, and the offset is also influenced by RF signal amplitude. The microwave circuit was enclosed in a small, fan-ventilated, plastic container that effectively eliminated temperature-induced mixer offset drift caused by ambient temperature fluctuations. A more detailed description of each component’s function within the circuit is given elsewhere (Branch, 1990).

Each branch of the microwave circuit was interfaced to an IBM-compatible PC-based analog and digital input/output board (Analog Devices MIO-120A) through the circuit shown in figure 2. The board’s analog output is
used to compensate for the mixer-induced offset (Powell et al., 1988).

No electromagnetic radiation hazard is associated with the operation of this system, because the maximum power density at the horn aperture will be less than 6 mW/cm². The United States standard exposure limit for extended periods (i.e., over 6-min duration) is 10 mW/cm² (ACGIH, 1983).

**Phase and Offset Adjustment**

To facilitate adjustment of phase difference and offset compensation, two variable attenuators (Narda model 792FM and HP model X382A) and a variable phase shifter (HP model X885A) were connected in series to represent the sample and holder. The HP attenuator was set at 25 dB during the phase-shift tests to represent a grain sample. The Narda attenuator, set at 11 dB, approximated the sample holder attenuation. A 90° phase difference at the mixer LO ports was obtained by: (1) arbitrarily setting the phase trimmers, (2) recording the mixer output voltages every 10° for 720°, (3) determining estimates for A, B, and C (PC-SAS Marquardt procedure) in:

\[ Y = A \sin(B + X) + C \]

where

- \( Y \) = mixer output (mV)
- \( A \) = sinusoidal amplitude (mV)
- \( B \) = phase-shift (deg)
- \( X \) = HP Phase Shifter setting (deg)
- \( C \) = offset (mV)

The phase shift, B, was determined for each of the sinusoids. If the phase difference, \( B_1 - B_2 \), was not 90° ±0.5°, the phase trimmers were adjusted and the procedure was repeated. Once set, the drift was typically not more than ±0.3°/2-h period.

Offset voltage compensation was checked by recording mixer output voltages every 10° for two cycles after an assumed offset voltage (based upon prior operational experience) was entered. The average of the 72 measured voltages should equal zero if the assumed offset was correct. If the average was a nonzero value, the offset voltage was corrected and the evaluation was repeated. The PC-SAS Marquardt procedure was used to estimate the needed offset correction (i.e., C); however, this procedure is time consuming, and the resulting offset correction estimates were essentially the same as those obtained by averaging the output voltages.

An evaluation as described by Powell et al. (1988) of accuracy and independence of phase shift and attenuation measurements was performed. The set phase shift and the measured phase shift for various attenuation levels were compared. A similar set of measurements was made for attenuation with several phase-shift values. Since the slope of each line was not significantly different from zero (95% confidence level), there was no interaction in the measurement of phase-shift and attenuation. Comparison of the mean of each line with the set value indicated no significant difference (95% CL). For an attenuation range of 0 to 40 dB, the attenuation and phase-shift accuracy was ±0.53 dB and ±5.56°, respectively. Most measurements were made at attenuation levels of 0 to 30 dB where the attenuation and phase-shift accuracy was ±0.23 dB and ±2.65°, respectively. These values represent the worst single case found among any of the lines and not the average accuracy of all lines combined.

**Material**

Soft red winter wheat of the Stacey cultivar, grown near Athens, Georgia, was used for these tests. The static tests were conducted with wheat harvested in the spring of 1989, which had a test weight of 738 kg/m³ (57.3 lb/bu) at 13.0% moisture content. (All moisture contents throughout this article are reported in wet basis.) The dynamic tests were conducted with wheat harvested in the spring of 1990, which had a bulk density of 783 kg/m³ (60.8 lb/bu) at 12.5% moisture content. The grain was cleaned with a VAC-AWAY vibrating screen seed cleaner. The upper screen had openings of 4.76 mm (3/16 in.) circular diameter, and the lower screen had openings of 1.59 mm (1/16 in.) X 11.11 mm (7/16 in.) rectangular dimensions.

Air was circulated through the grain to condition it to the desired test moisture content. When conditioning large quantities for the dynamic tests, the grain was circulated to provide more uniform wetting. Water was dripped onto the recirculating grain when needed to speed the re-wetting process. After conditioning, the grain was allowed to stand from 12 to 36 hours to allow for equilibration. Moisture content was determined by oven drying according to ASAE Standard S352.2 (1989).

**Static Testing**

During static testing, microwave measurements were taken on wheat confined in a sample holder located between two horn antennas. The sample holder was 17 cm tall and had a cross-section of 12 x 13 cm. The sample holder was constructed of 1-cm (3/8-in.) thick Plexiglas and had a volume of 1760 cm³ (0.05 bushel). The sample holder had dimensions which were 3.5 times the horn openings in both directions. The 10-cm sample thickness, as recommended by Powell et al. (1988), yields an attenuation within system measurement capability. The dielectric constant of Plexiglas is approximately 2.6 with a loss factor of approximately 0.02 at 10 GHz. The 1-cm Plexiglas is approximately 1/2 wavelength thick at the operating frequency, which should minimize the signal reflections caused by the air-surface interface.

To evaluate the performance of the microwave moisture measuring system, grain samples with 11 different initial bulk densities were tested. Three of the samples were comprised entirely of wheat, while the remaining eight samples were comprised of a wheat and styrofoam bead mixture. The three wheat-only samples were achieved by (1) loosely filling the sample holder, (2) loosely filling and lightly tamping the sample holder, and (3) shaking the sample holder during filling and then tamping. The remaining eight test samples consisted of a mixture of wheat and styrofoam beads. The styrofoam beads were used to create void spaces between the grain kernels and thus lower the bulk density of the sample. Styrofoam beads with a dielectric constant of about 1.05 and a negligible loss factor collected between No. 6 mesh (3.36 mm) and No. 8 mesh (2.38 mm) standard sieve screens, were used. The average spherical diameter, as defined by Kunii and Levenspiel (1969), of a wheat kernel was 4.07 mm. The
wheat and styrofoam were combined volumetrically to yield mixtures with densities varying from 0.15 g/cm³ to 0.80 g/cm³ in increments of 0.07 g/cm³. The density of the sample was determined by weighing the container of known volume filled with the test material.

The difference in the specific gravity of wheat and styrofoam caused the styrofoam beads to move upward which made mixing difficult. To achieve a relatively uniform mixture, the styrofoam and wheat were placed in alternating layers with thicknesses corresponding to the desired mixture ratio. After each two or three layers, the sample was stirred with an aluminum rod until the mixture appeared uniform. Even though the dielectric properties of styrofoam are similar to air, a small phase shift of about 9° was measured when the sample holder was filled with 100% styrofoam. To account for this, the phase shift caused by the styrofoam was subtracted from each measurement. The amount of correction was based upon the volumetric portion of styrofoam, assuming a linear variation from 9° for 100% styrofoam to 0° for the empty sample holder.

For the samples with wheat only, four replications were performed per moisture content and density level. For the samples with the wheat/styrofoam mixture, six replications were performed per moisture content and density level because of the nonuniformity of the mixture which produced greater variability.

**DYNAMIC TESTING**

During dynamic testing, continuous moisture measurements were taken of a stream of flowing grain discharged from a 0.7 m³ (20 bushel) storage bin (fig. 3). The bin was constructed with a perforated metal hopper to facilitate conditioning of the grain for testing. The hopper slope was approximately 70° to provide for mass flow discharge conditions within the bin to help eliminate particle segregation during flow. As the grain flowed from the bin, it fell through a 100-cm long, 10-cm × 11-cm rectangular Plexiglas duct. During discharge from the bin, the flowing grain tended to aerate itself and disperse, thus causing a variation in its bulk density. A density range from 0.4 g/cm³ to 0.1 g/cm³ was obtained in the free fall test. The flow rate varied slightly with grain moisture content.

The actual density of the material was difficult to determine during the free-fall test. The theoretical density for free-falling grain was predicted as follows:

\[
\rho_F = \frac{Q}{A \times V_H} \tag{4a}
\]

\[
V_H = V_o + V_A \tag{4b}
\]

\[
V_A = \sqrt{(2 \times g \times H)} \tag{4c}
\]

\[
V_o = \frac{Q}{A \times \rho_B} \tag{4d}
\]

where

- \( \rho_F \) = material density during fall (g/cm³)
- \( \rho_B \) = bulk density at orifice (g/cm³)
- \( Q \) = material flow rate (g/s)
- \( A \) = cross-sectional area (cm²)
- \( H \) = height of fall from orifice to center of horns (cm)
- \( V_H \) = velocity at a given height (cm/s)
- \( V_o \) = initial material velocity at orifice (cm/s)
- \( V_A \) = velocity produced by acceleration (cm/s)
- \( g \) = gravitational constant (981 cm/s²)

Verification of the theoretical analysis was attempted using a 100-cm long, 10-cm × 11-cm cross-section Plexiglas duct with grooves cut at 5-cm intervals along its length. Sliding partitions were used to capture the amount of material within the 550-cm³ volume between the two partitions at selected intervals along the length of the tube. A comparison of the theoretical and experimental densities (fig. 4) shows that a higher density was predicted than was measured. By video taping the operation (0.001-s shutter speed), it was noted that the time required to insert the sliding partitions within the duct affected the amount of grain collected. The shorter the insertion time, the larger the amount of grain collected and the higher the calculated density levels. The theoretical calculation depends upon the bulk density of a static sample of grain at the orifice, which was assumed to be the uncompacted bulk density of a sample of grain. However, during discharge from a bin, the material expands vertically and aerates itself, thus producing a slightly smaller bulk density at the orifice. Therefore, this assumption overpredicts the bulk density of the grain at the orifice and in the column of falling grain, and the actual density in the column of falling grain is probably between the experimental and the theoretically predicted values.

Evaluations at lower densities, e.g., 0.22 g/cm³, during free-fall were desired; however, there was extreme
nonuniformity in the grain distribution in the cross-section between the horns. This nonuniformity results from flow concentration in the duct caused by the Magnus effect (Gerhart and Gross, 1985). The velocity differential across the cross-section creates a force, the Magnus force, that tends to lift or direct the kernel toward the side with the greater velocity (i.e., toward the center of the stream). For drop distances from 8 to 26 cm, the grain was relatively well distributed over the cross section between the horns.

For solid flow tests (i.e., grain not allowed to free-fall), the flow rate was reduced by placing an orifice at the bottom of the Plexiglas duct. Microwave measurements were also taken of dense phase material in plug flow moving within a duct. Flow rates obtained from orifices 3.8 cm (1.5 in.), 6.4 cm (2.5 in.), and 8.9 cm (3.5 in.) in diameter were tested. Attenuation and phase-shift measurements were made 34 cm down from the top of the sample duct.

**CALIBRATION CURVE DEVELOPMENT**

A nonlinear regression analysis of the phase-shift/attenuation ratio on moisture content, as recommended by Kraszewski (1988), with data from the static and dynamic testing was conducted to select the best equation to fit the data. Attenuation values were grouped by both density and moisture content. A box-plot test was used to verify statistically the elimination of outliers (Ott, 1988). In addition to the statistical evidence, there must also be sufficient cause for suspecting that the data point is an outlier before it can be discarded. In the static tests, deletion was based upon suspicion of mixture nonuniformity. No data points were removed in the dynamic tests, since no basis for removal was evident.

The data were grouped by moisture content, and then the density independence of phase shift/attenuation was statistically evaluated. The accuracy of moisture content prediction equations was then determined. Kraszewski (1988) suggested three density-independent equations and the corresponding equation for the uncertainty of moisture content measurement. The relationship between moisture content and parameter X in each of the moisture content prediction equations can be expressed with almost equal statistical significance. For this research, the regression is reported for only the following equation:

\[
M = \frac{a}{X} + b
\]  

\[
\Delta M = -(M-b) \left( \Delta \eta/\eta + \Delta \phi/\phi \right)
\]  

where

- \( M \) = moisture content (% w.b.)
- \( \Delta M \) = uncertainty of moisture content measurement (% w.b.)
- \( \eta \) = attenuation measured (dB)
- \( \Delta \eta \) = uncertainty of attenuation measurement (dB)
- \( \phi \) = phase shift measured (deg)
- \( \Delta \phi \) = uncertainty of phase shift measurement (deg)
- \( X \) = parameter, phase shift/attenuation (deg/dB)
- a and b = parameter estimates for the predictive equations

**RESULTS**

Values of the numerical coefficients for wheat in both the static and dynamic condition are shown in table 1 using the technique described by equation 5a. In addition, results using similar techniques are shown by Kraszewski (1988) and Kraszewski and Nelson (1991).

For the static test condition and material densities of 0.73 to 0.81 g/cm\(^3\), the technique described by equation 5a was used to determine R\(^2\) of 0.98 was determined using equation 5a. The results are very similar to those of Kraszewski (1988) and Kraszewski and Nelson (1991) over similar static test conditions and material densities. However, over the total range of material densities tested (0.23 to 0.81 g/cm\(^3\), the

<table>
<thead>
<tr>
<th>Type of Test</th>
<th>Wheat Cultivar</th>
<th>Frequency (GHz)</th>
<th>Density Range (g/cm(^3))</th>
<th>Numerical Coefficients</th>
<th>Coefficient of Determination (R(^2))</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static</td>
<td>Wheat only</td>
<td>Stacey</td>
<td>9.6</td>
<td>0.73 to 0.81</td>
<td>386.02, 5.57</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>Wheat/</td>
<td>Stacey</td>
<td>9.6</td>
<td>0.23 to 0.81</td>
<td>340.01, 6.66</td>
<td>0.84</td>
</tr>
<tr>
<td></td>
<td>styrofoam</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wheat</td>
<td>Grana 75</td>
<td>9.0</td>
<td>0.72 to 0.79</td>
<td>457.52, 3.75</td>
<td>0.99</td>
<td>Kraszewski (1988)</td>
</tr>
<tr>
<td>Wheat</td>
<td>Stacey</td>
<td>9.0</td>
<td>0.72 to 0.87</td>
<td>440.27, 7.57</td>
<td>0.97</td>
<td>Kraszewski and Nelson (1991)</td>
</tr>
<tr>
<td>Dynamic</td>
<td>Solid flow</td>
<td>Stacey</td>
<td>9.6</td>
<td>0.72 to 0.78</td>
<td>459.40, 2.22</td>
<td>0.95</td>
</tr>
<tr>
<td></td>
<td>Solid flow and free-fall</td>
<td>Stacey</td>
<td>9.6</td>
<td>0.22 to 0.78</td>
<td>321.75, 5.80</td>
<td>0.79</td>
</tr>
</tbody>
</table>
accuracy of this prediction technique was much lower with an $R^2$ of 0.84.

For the dynamic test condition (grain moving in a pipe), similar trends were observed using equation 5a. For bulk densities between 0.72 and 0.78 g/cm$^3$ (solid flow) equation 5a predicted accurately the moisture content of the flowing material. For this set of test conditions an $R^2$ of 0.95 was determined. However, over the total range of material densities tested (0.22 to 0.78 g/cm$^3$) the accuracy of this prediction technique was much lower with an $R^2$ of 0.79.

During both static and dynamic tests decreased accuracy was observed over the wider range of material densities. This decrease in accuracy may not only be associated with the prediction technique but also with: (a) the microwave circuit used to measure the moisture contents, and (b) the ability to duplicate material densities and moisture contents during different replications. For material densities between 0.72 and 0.81 g/cm$^3$, the system was able to predict accurately the moisture content of both static and dynamic grain samples and the bulk densities were easily reproduced from one test to another. However, for conditions in which the grain sample was aerated (dynamic-free fall) or mixed with styrofoam beads (static testing) the accuracy of the test technique to duplicate this condition from replication to replication as well as the system accuracy decreased.

**STATIC TEST ANALYSIS**

The static test analysis was completed with data for moisture contents from 11 to 19% and density ranges from 0.22 to 0.80 g/cm$^3$. Data taken at 9% moisture content and 0.15 g/cm$^3$ had excessive scatter and were not included in the final data set. The suspected cause of the scatter was the microwave multiple reflections resulting from the lack of attenuation in the low moisture content and low density levels. The interrelationship of attenuation and phase shift with density is illustrated in figures 5 and 6. The variation between replications was much smaller for the samples comprised entirely of wheat, the three highest densities, than for the wheat and styrofoam mixtures, the seven lower densities. Since the dielectric properties of styrofoam are close to those of air, the mixture uniformity apparently affects the measurements. The lines have intercepts close to zero and correlation coefficients from 0.84 to 0.94 for attenuation and 0.81 to 0.94 for phase shift. The values of phase shift were selected in 180° intervals (eq. 2). Data points within a density group occasionally varied by more than 200° and a better fit could have been obtained with a different choice. However, the phase shift was selected based upon the projected phase-shift/attenuation parameter value determined for wheat-only samples at particular moisture contents. The large variation in attenuation associated with the lower densities required large variation in phase shift values to yield a phase shift/attenuation comparable to projected phase shift/attenuation values.

For the wheat-only densities, the relationship between phase-shift/attenuation and moisture content (fig. 7) is accurately described by equation 5a ($R^2 = 0.9849$). The curvature, $a$, is comparable to that reported by Kraszewski and Nelson (1991) and the intercept, $b$, is only slightly different (refer to table 2). The data confidence intervals indicate a moisture content measurement accuracy of ±0.68% (95% confidence level). The accuracy for equation 5a as determined by equation 5b was ±0.14%. This compares favorably to the confidence interval of ±0.15% for equation 5a based on the SAS GLM option.
The scatter introduced by the nonuniformity of the wheat and styrofoam mixture is apparent when the full range of densities is included (fig. 8). The confidence intervals indicate a moisture content measurement accuracy of approximately ±2.1%. However, the slope of phase-shift/attenuation ratio versus density is not significantly different from zero (fig. 9) even though the data are somewhat scattered.

**Dynamic Analysis**

Moisture contents and densities from 11 to 19% and 0.22 to 0.79 g/cm³, respectively, were included in the dynamic tests. During sampling, from 0.5 to 14.3 kg of material, depending on the orifice size, passed between the horns while obtaining one data point (e.g., 10 readings/data point in 2.08 s).

It is apparent from the plots of both attenuation and phase shift versus calculated density (figs. 10 and 11) that the curves do not intersect the x-axis near zero, which indicates an overestimation of density. This is believed related to both (a) the technique used to calculate density, and (b) the ability to sample data over the entire range of bulk densities. In estimating the bulk density of the moving sample of grain the technique (eq. 4a) used to calculate the density, ρp, assumes that the velocity, Vp, at a discrete point is a function of the velocity at the orifice, v₀, plus the additional velocity obtained during free fall, vₐ. The velocity, v₀, is believed to be a function of the material flow rate, Q, and the bulk density at the orifice, ρB, (eq. 4d). The bulk density at the orifice of the bin, ρB, was assumed to be equal to the uncompacted bulk density of a sample of grain. However, as material is discharged from a bin, the material expands vertically and aerates itself, thus the bulk density at the orifice is slightly smaller than that initially assumed. In addition, the density of the sample was varied by changing the distance from the discharge orifice to the center axis of the horns of the microwave circuit (fig. 3). Additional data points between densities of...
0.79 g/cm³ and 0.42 g/cm³ were not possible because of the limitations caused by the Plexiglas duct shown in figure 3. This limitation prevented a more accurate determination of the curve over the full density range. There was more scatter for the solid-flow test than existed for the wheat-only static test. This was believed to be caused by both small variations in the moisture content and the density variation in the flowing grain caused by changing flow patterns. For these experiments sample sizes of from 0.5 to 14.3 kg of grain were used during any given test. While standard procedures were used to adjust the grain moisture it is therefore, the greater density variations. This results in additional scatter for high attenuation values at the higher moisture contents.

The relationship of phase-shift/attenuation ratio to moisture content for solid-flow densities (fig. 12) is well behaved (R² = 0.9525), and the curve parameters, a and b (Table 2), compare favorably with those of Kraszewski (1988). The data confidence intervals indicate a moisture content measurement accuracy of ±1.17% (95% confidence level). The accuracy for equation 5a as determined by the SAS GLM option.

The relationship of phase-shift/attenuation ratio to moisture content for the dynamic flow measurements (fig. 13 and table 3) illustrates the scatter introduced by including the free-fall densities, especially at the lower moisture content levels. The confidence intervals indicate a moisture content measurement accuracy of + 2.46%.

The relationship of the phase-shift/attenuation ratio to density (fig. 14 and table 3) indicates that the ratio is not entirely density independent. Figure 14 indicates less...
Figure 14—Mean phase-shift/attenuation values as a function of density for all dynamic test data. \( \bar{X} \) is the overall mean value for a given moisture content, while \( \bar{x} \) is the mean value for a discrete density and moisture content.

sensitivity of the phase-shift/attenuation ratio to density at the higher moisture contents.

CONCLUSIONS

The microwave system for measuring phase shift and attenuation was greatly improved over the version used by Powell (1987). The modified system is more accurate and compact. System calibration identified attenuation levels from 10 to 40 dB as an acceptable operational range. However, the reflections created within the sample holder at low attenuation levels (i.e., <5 dB) restrict the ability to extend the measurements to lower extremes.

Calibration curves for both static and dynamic wheat samples were developed. Comparisons of calibrations from collected data and from the literature agreed well, and equations from both predicted relatively well the moisture content of static wheat samples. Similar type results with somewhat reduced accuracy were obtained in dynamic solid-flow tests on wheat. During dynamic testing, as the density range was reduced, the scatter became more apparent. For solid-flow conditions the measurement appeared to be independent of density.

Moisture content predictability of ±0.7% was achieved for the static tests on wheat. In dynamic solid-flow tests moisture content predictability of ±1.2% was achieved.

Density-independent moisture content measurements can be made on wheat within certain density ranges (0.72 to 0.81 g/cm³). Static tests on wheat yielded the best results, while dynamic solid-flow tests also indicated potential for making density-independent measurements.

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