Microwave resonator for sensing moisture content and mass of single wheat kernels

A.W. KRASZEWSKI and S.O. NELSON


Kraszewski, A.W. and Nelson, S.O. 1994. Microwave resonator for sensing moisture content and mass of single wheat kernels. Can. Agric. Eng. 36:231-238. Principles for determining moisture content and mass of individual wheat kernels by microwave resonator measurements are discussed and data are presented showing the application of these principles. By measuring the shift in the resonant frequency and the change in the resonator transmission characteristics when a wheat kernel is inserted into the resonator, moisture content of the kernel may be determined independent of its mass and apparently independent of wheat variety. The same measurement can simultaneously determine the kernel mass. Moisture contents in the range from 10 to 21%, wet basis, were determined with an uncertainty of 0.8% moisture. Uncertainty in the mass determination was less than 1 mg.

Keywords: moisture content, wheat, electromagnetic waves, kernel mass, microwave measurement

M = \frac{\text{mass of water}}{\text{mass of wet material}} \times 100 \text{ [%]} \tag{1}

INTRODUCTION

Moisture content is one of the most important factors determining quality of agricultural products during harvesting, storage, trading, and processing. Because excessive moisture levels will cause product spoilage, drying of agricultural products is a common practice. Drying is always an expensive process because of equipment and energy costs. Overdrying of agricultural products not only wastes energy, but also can result in deterioration in quality and nutritional value.

As a low-cost alternative to drying, high-moisture grain is often blended with lower moisture grain to achieve a desired average moisture content. If mixing is incomplete, pockets of high moisture grain may spoil over time. Thus, monitoring and control of moisture content distribution as well as its level is important at all stages.

The moisture content of a material, \( M \), expressed in percentage wet basis, is defined as:

Standard laboratory methods of moisture content determination in grain are based directly on this definition (ASAE 1993). The mass of water is removed from small samples of wet material (several grams) by evaporation. Weighing the sample before and after drying yields the required information. Too often it is assumed that grain is homogeneous and uniform, that water is evenly distributed throughout the lot of material, and that differences in moisture content determinations arise from the uncertainties in weighing. Such ideal materials are rarely found in nature and moisture variation in large-scale industrial processes is often a serious problem.

Moisture content of a given grain lot is always represented by a single number, at most averaged for several samples, and is rarely accompanied by data on the deviation or range of values for those samples. Standard methods may yield identical moisture content for the three different moisture distributions shown in Fig. 1. This is especially important for grain, when the situation shown in Fig. 1c (a mixture of two lots of different moisture levels) can lead to spoilage. To evaluate moisture distributions among kernels in grain samples, a single-kernel moisture tester is required.

Single-kernel moisture meters based on direct current (DC) conductivity or radio frequency (RF) impedance measurements at frequencies of 1 to 5 MHz have been developed for corn (Watson et al. 1979; Nelson and Lawrence 1989; Kandala et al. 1989), but we have found (Kraszewski et al. 1989; Kraszewski and Nelson 1993) that microwave resonant cavity measurements provide an interesting alternative, because they are fast, accurate, nondestructive, and do not require physical contact between the kernel and measuring equipment. The purpose of this research was to determine the effects of wheat kernels of random shapes and dimensions and different moisture levels on the measured parameters of a microwave resonator and to evaluate this technique for determining the moisture content and mass of individual kernels. A two-parameter microwave measurement technique has been previously adapted for simultaneous determination of moisture content and bulk density in wheat (Kraszewski and Nelson 1992). In this paper, an extension of this concept, using different microwave measurement techniques, is applied to single wheat kernels.
THEORETICAL BACKGROUND

A dielectric region completely surrounded by a conducting surface constitutes a resonant cavity or resonator. A simple cavity can be created with a hollow rectangular or circular waveguide. If a section of such a waveguide is sealed with a short-circuiting conductive wall perpendicular to the direction of wave propagation, the incident and reflected waves are superimposed and create a standing wave. The tangential electric field and normal magnetic field are zero at this wall and at distances of integral half-wavelengths from it. In such a nodal plane, a second conductive wall can be located without disturbing the standing wave. Waves reflected by the first short-circuiting wall will be reflected back by the second short-circuiting wall to coincide with the incident wave, and a resonant cavity results in which waves are reflected back and forth, and a standing-wave pattern persists if energy is supplied to offset losses in the cavity. If the cavity is excited at the proper frequency, through a coupling hole for example, the fields can build up within the cavity in certain restricted configurations or modes of operation.

An example of a resonant cavity made from a section of rectangular waveguide, short-circuited at each end with metal plates containing circular coupling holes and filled with air as the dielectric, is shown in Fig. 2. The cavity will be resonant at frequencies having an integral number of half wavelengths in the waveguide, \( \lambda / 2 \), equal to the length, \( L \), i.e. \( L = p \lambda / 2 \), where \( p = 1, 2, 3 \ldots \) is an integer. Thus, when a cavity similar to that shown in Fig. 2 is connected to a swept oscillator and a detector to register transmission as a function of frequency, the general picture at the output is similar to that presented in Fig. 3. Peaks of transmission through the cavity occur at frequencies for which \( p = 3, 4, 5, \) and \( 6 \) for a given length of the cavity and for the sweep-frequency range shown in Fig. 3. These are the resonant frequencies for the different modes of cavity operation designated as the TE\(_{10p} \) modes. This indicates that the electric field vector, \( E \), is transverse to the \( z \) direction of propagation in the waveguide. The first subscript indicates one half-cycle of the \( E \)-field pattern in the \( x \) direction across the \( a \) dimension of the waveguide, the second subscript indicates no \( E \) field in the \( y \) direction across the \( b \) dimension, and the third subscript indicates the value of \( p \), the number of half-wavelengths along the \( z \)-axis within the length \( L \) of the cavity. Since the tangential component of the electric field must vanish at the conducting boundaries, the \( E \) field will have a maximum value at the center of the cavity for the TE\(_{101} \) mode or for any TE\(_{10p} \) mode for which \( p \) is an odd integer.

Resonant cavities have been widely used for determining the microwave properties of material samples by measuring the shift in the resonant frequency and the change in the \( Q \) factor of the cavity when a sample is inserted into the cavity.

Fig. 1. Examples of different moisture-content distributions.

![Diagram of a rectangular waveguide resonant cavity showing object at center of cavity and coupling hole in short-circuiting wall.](image)
Fig. 3. Multiple resonances in a rectangular waveguide cavity operating in the X band.

(Altschuler 1963; Waldron 1967). Measured parameters depend upon the volume, geometry, and mode of operation of the cavity, as well as the permittivity, shape, dimensions, and location of the object inside the cavity. For a given cavity and material sample of regular (analytical) shape and well-defined dimensions, one can determine the permittivity of the material. This technique may be demonstrated using an expanded view of the resonant curve corresponding to \( p = 5 \) in Fig. 3 as shown in Fig. 4. The resonance of the cavity appears as a peak in transmission through the cavity. To determine the resonant frequency, the frequency of a signal coupled to the cavity is varied until the maximum transmission is observed. The second parameter of the resonant curve, as shown in Fig. 4, is its shape. The apparent \( Q \) factor of the cavity depends upon energy losses in the cavity (walls, coupling, etc.). Thus when an object is introduced into the cavity, the resonant frequency will decrease and the \( Q \) factor will be lowered, causing a broader, flatter resonant curve.

Thus, referring to Fig. 4, the shift of resonant frequency is denoted as \( \Delta F = f_o - f_s \), where subscripts \( o \) and \( s \) refer to the empty cavity and the cavity loaded with an object at the center of the cavity, respectively. Energy dissipated in the object is related to the change in the cavity \( Q \) factor:

\[
\frac{1}{Q_s} - 1 = \frac{1}{Q_o} \left( \frac{V_o}{V_s} - 1 \right) = \frac{\Delta T}{Q_o},
\]

where:
- \( V \) = voltage transmission coefficient at resonance,
- \( \Delta T = (10^6 - 1) = \) transmission factor,
- \( k = 0.05 (S_{21o} - S_{21s}) \), and
- \( S_{21} = \) voltage transmission coefficient at resonance (db).

These cavity parameters are related to the dielectric properties of the object by the perturbation equations (Kittel 1956; Waldron 1967):

\[
\Delta F = 2(e' - 1) K f_o \left( \frac{V_s}{V_o} \right)
\]

\[
\Delta T = 4e'' K^2 \left( \frac{V_s}{V_o} \right),
\]

where:
- \( e^* = e' - je'' = \) material permittivity,
- \( e' = \) dielectric constant,
- \( e'' = \) loss factor,
- \( V_s = \) volume of sample,
- \( V_o = \) volume of empty cavity, and
- \( K = \) factor dependent upon object shape, orientation, and permittivity.

\( K \) can be expressed as:

\[
K = 1 + A (e' - 1),
\]

where \( A = \) depolarization factor along the kernel axis parallel to the \( E \)-field vector. For a sphere, \( A = 1/3 \) and \( K \) has a value of \( 3/(e' + 2) \). For thin rods parallel to the electric field, \( A = 0 \) and \( K = 1 \). For a thin disk perpendicular to the electric field, \( A = 0 \) and \( K = 1/e' \). Equations 3 and 4 can be used for material permittivity measurements when the object is of well-defined dimensions and shape, and the values of \( f_o, Q_o, \) and \( V_o \) are known for a given cavity, under the assumption that the volume of the object is much smaller than the volume of the cavity, and the object itself has relatively low loss (\( e''^2 >> e''^2 \)). Both of these conditions are relatively easy to satisfy for solid dielectric materials that can be conveniently machined and measured. However, for biological materials such as tissue, seeds, and kernels, these conditions cannot usually be fulfilled satisfactorily and the resonant cavity techniques are not useful for permittivity measurements of those materials.

However, it has been previously shown for soybeans and peanuts that, when a kernel is inserted into the cavity, two cavity parameters, the shift of the resonant frequency, \( \Delta F \), and the change in the transmission factor, \( \Delta T \), are linearly related to the mass of water, \( m_w \), and the mass of dry matter, \( m_d \), in the seed or kernel (Kraszewski et al. 1989; Kraszewski
and Nelson 1993). This may be expressed in the general form:

$$\Delta F = a + bm_w + cm_d$$  \hspace{1cm} (6a)

$$\Delta T = d + gm_w + hm_d,$$  \hspace{1cm} (6b)

where \(a, b, c, d, g,\) and \(h\) are numerical factors determined experimentally for a given kind of kernel. Equations 6a and 6b can be solved to express the mass of water and mass of dry material in the kernel in terms of the two measured resonant cavity parameters in the form:

$$m_w = \frac{c(\Delta T - d) - h(\Delta F - a)}{cg - bh}$$  \hspace{1cm} (7a)

$$md = \frac{g(\Delta F - a) - b(\Delta T - d)}{cg - bh}$$  \hspace{1cm} (7b)

The mass of the moist kernel, \(m_m\), can be written as:

$$m_m = m_w + md = \frac{(\Delta F - a)(g - h) + (\Delta T - d)(c - b)}{cg - bh}$$  \hspace{1cm} (8)

and its moisture content, \(M\), determined on the wet basis, is:

$$M = \frac{m_w}{m_w + md} \times 100$$

$$= \frac{c(\Delta T - d) - h(\Delta F - a)}{(\Delta F - a)(g - h) + (\Delta T - d)(c - b)} \times 100 \text{ [\%]}$$  \hspace{1cm} (9)

Both Eqs. 8 and 9 contain only the resonant cavity parameters determined experimentally and are valid under the assumption that the volume of the object is much smaller than the volume of the cavity \((v_o \sim 0.001 v_v)\). When this condition is not met, the concept of using two simultaneous microwave measurements is still valid, but Eqs. 6a and 6b are nonlinear and the solution may be more troublesome.

Thus, the measurement of the coordinates of the peak of the resonant curves (Fig. 4), with and without the kernel inside the cavity, provides enough information to determine the moisture content and mass of the kernel. The simplicity of the technique, as well as its nondestructive character and the simplicity of Eq. 9 for use as a calibration equation for moisture content, is so attractive that many attempts have been made to assess its practical usefulness.

**MATERIALS AND METHODS**

Four lots of wheat, *Triticum aestivum* L., were used in the study. 'Coker 9733' soft red winter wheat, grown in Georgia in 1989, and 'Karl' hard red winter wheat, grown in Nebraska in 1992, were selected for calibration measurements. Test weight (bulk density under specified conditions) at 24°C for Coker at 12.8% moisture was 795 kg m⁻³ and for Karl at 12.1% moisture was 755 kg m⁻³. To obtain moisture levels higher than the initial moisture content, samples were conditioned by adding distilled water, sealing them in jars, and holding them at 4°C for at least a week prior to measurement. Before the measurements, samples were held in jars for about 16 h at room temperature (23°C) and then several kernels were randomly selected and sealed individually in small glass vials just prior to the measurements. After the measurement, the kernels were immediately returned to the vials before being weighed and dried. Similar procedures were used during the verifying measurements that were carried out on 'Stacy' soft red winter wheat grown in Georgia in 1988 and on 'Arapahoe' hard red winter wheat harvested in Nebraska in 1992. Respective test weights at 24°C were 786 and 770 kg m⁻³ recorded at moisture contents of 12.0 and 12.5%.

Moisture contents of individual kernels were determined by forced-air oven drying for 19 h at 130°C as prescribed by standards for unground bulk samples of wheat (ASAE 1993). Upon removal from the oven, all kernels were cooled in a desiccator over anhydrous CaSO₄ before being weighed.

Most of the wheat kernels tested had lengths between 5.2 and 6.2 mm and average diameters of 2.3 to 3.1 mm. The length/diameter ratios ranged from 1.85 to 2.49, 1.93 to 2.57, 2.09 to 2.52, and 2.15 to 2.62 for the 'Stacy', 'Coker', 'Arapahoe' and 'Karl' lots, respectively.

Any kind of microwave resonator may be used for determining the moisture content of perturbing objects; however, a rectangular waveguide resonant cavity is one of the simplest and easiest to build. Principles of a resonator general perturbation theory (Waldron 1967) can be used to establish some general rules of resonant cavity applications for wheat. In standard rectangular waveguide cavities, the object-to-cavity volume ratio should be < 10⁻³. The resonant cavity used in this study consisted of a section of standard X-band WR-90 rectangular waveguide (inside dimensions: 22.86 x 10.16 mm) 91.5 mm long. It was coupled with external waveguides through a coupling hole 7.1 mm in diameter at each end of the cavity. A Teflon, thin-wall, 3.73-mm o.d. tube was installed through the center of cavity to facilitate positioning the kernel at the center of the cavity. The resonant frequency of the empty cavity operating in the TE₁₀₅ (H₁₀₅) mode was \(f_0 = 10,526.7\) MHz and its \(Q\)-factor \((Q_0)\) was 900. The cavity was located between two waveguide-to-coaxial transitions, as shown in Fig. 5, which allowed it to be connected to a computer-controlled automatic network analyzer calibrated in the transmission mode. The analyzer generated 801 discrete frequencies within a range of 96 MHz. In this way, reading the coordinates of the marker on the test-set CRT display, provided measurements of the transmission through the cavity in increments of 0.12 MHz. A “marker-to-maximum” command

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**Fig. 5. Block diagram of the measuring setup.**
automatically accomplished the determination of the coordinates of the peak of the resonant curve (resonant frequency, \(f_0\), and transmission loss, \(S_{21}\), in Fig. 4), without and with an object located in the cavity, providing all information necessary to determine the two measured quantities \(\Delta F\) and \(\Delta T\).

**EXPERIMENTAL RESULTS**

Experimental results for 474 wheat kernels measured at various moisture levels from 9.7% to 20.8% at 24°C in the X-band resonant cavity are shown in Figs. 6 and 7. The shift of resonant frequency, \(\Delta F\), as a function of the mass of water, \(m_w\), is presented in Fig. 6, while the transmission factor, \(\Delta T\), versus the mass of water is shown in Fig. 7. Two linear equations fit the experimental results as follows:

\[
\Delta F = 4.58 + 6.8656 m_w + 0.5842 m_d \quad r = 0.9856 \quad (10a)
\]

\[
\Delta T = -0.533 + 0.6835 m_w - 0.0311 m_d \quad r = 0.9741 \quad (10b)
\]

where \(m_w\) and \(m_d\) are expressed in milligrams, and \(r\) is the correlation coefficient. Following Eqs. 6 - 9, these two equations can be solved simultaneously for \(m_w\) and \(m_d\) to provide the calibration equations for the wet kernel mass, \(m_w\), and kernel moisture content, \(M\), in the form:

\[
m_w = 1.0958 \Delta F - 9.3473 \Delta T - 8.682 \quad [mg] \quad (11)
\]

\[
M = \frac{100 m_w}{m_w + m_d} = \frac{5.9285 \Delta F + 77.2464 \Delta T + 17.657}{1.096 \Delta F - 9.3473 \Delta T - 8.682} \quad [%] \quad (12)
\]

Equations 11 and 12 were then used to calculate the wet masses of individual kernels and their moisture contents, respectively, from the resonant cavity measurements. To verify the accuracy of the determination, another 534 kernels of different cultivars that were harvested in different years were tested in the same resonator. The moisture contents of those kernels ranged from 9.4% to 21.5%. The moisture contents of kernels were determined by the standard oven method and compared with those calculated from Eq. 12. The result of the comparison is shown in Fig. 8. Similarly, the masses of these kernels were compared with those predicted by Eq. 11 and results of those comparisons are shown in Fig. 9. The histogram presented in Fig. 10 shows the distribution of differences between the measured moisture contents and moisture contents predicted from Eq. 12 for the 534 wheat kernels. The predicted values of wheat kernel moisture content agreed well with those determined by the standard method. The standard error of performance (SEP) (the standard deviation of the differences) for the method was 0.79% moisture content, as determined by:

\[
SEP = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (\Delta M_i - \Delta M)^2} \quad (13)
\]

where:

- \(\Delta M_i\) = difference in moisture content between the value predicted from Eq. 12 and that of the air-oven determination for the \(i\)-th kernel, and
- \(N\) = number of kernels observed.

The mean value of the differences (bias)

\[
\Delta M = \frac{1}{N} \sum_{i=1}^{N} \Delta M_i \quad (14)
\]

was -0.12% moisture. It should be noted that the uncertainty in the standard oven moisture determination (as calculated below) is 0.2 to 0.3% moisture content.

The histogram presented in Fig. 11 shows the distribution of differences between the measured mass (weight) and that predicted from Eq. 11 for the 534 wheat kernels. The predicted values of wheat kernel mass agreed with those determined by weighing with an accuracy better than \(\pm 1\) mg.
(standard deviation) over the whole range of moisture content from 9.4 to 21.5%, with a bias of 0.1 mg. The predicted values of wheat kernel moisture content and their mass agree well with those determined by the standard methods.

**UNCERTAINTY ANALYSIS**

The accuracy of system calibration is affected by an uncertainty of the measuring system, $\sigma_M$, consisting of the repeatability of the results for the same kernel of given moisture content and an uncertainty in the "real" values of the moisture content determination, $\sigma_r$. The latter is a measure of the repeatability of the results provided by the standard oven method used for the system calibration. Since both of these magnitudes are of random character, the uncertainty in using the microwave resonant cavity for moisture content determination in a single kernel may be defined as:

$$\sigma_k = \sqrt{\sigma_M^2 + \sigma_r^2}$$  \hspace{1cm} (15)

Another source of error of systematic character is related to the model limitations. Some of those errors caused by shape variations among the kernels are discussed in the next paragraph.

The uncertainty in the mass measuring system can be determined by differentiation of Eq. 8, which gives:

$$\Delta m = \sigma_m = \frac{(g - h)}{cg - bh} \delta(\Delta F) + \frac{(c - b)}{cg - bh} \delta(\Delta T)$$  \hspace{1cm} (16)

and for the moisture content measuring system by differentiation of Eq. 9:

$$\Delta M = \sigma_M = \frac{(sg - bh) [(\Delta F - a) \delta(\Delta T) - (\Delta T - d) \delta(\Delta F)]}{[(\Delta F - a) (g - h) + (\Delta T - d) (c - b)]^2}$$  \hspace{1cm} (17)

where the uncertainties in the variable measurements are defined as:

$$\delta(\Delta F) = \delta F = n_1 \delta f$$  \hspace{1cm} (18a)

$$\delta(\Delta T) = B (\delta S_0 + \delta S_2) = B n_2 \delta S_2$$  \hspace{1cm} (18b)

and $B = 2.303 \times 10^5/20 = 0.115 (\Delta T + 1)$, and $\delta f$ and $\delta S$ are the elementary errors in the resonant frequency measurement and the transmission coefficient measurements, respectively, with an integer $n = 0, 1, 2, 3, \ldots$. The discrete character of the measurements causes a similar distribution of errors. Because there is no continuous spectrum of readings available, the error in the resonant frequency measurement, $\delta f$, may have a value of $\delta f/2$ or any multiple $n$ thereof, where $\delta f$ is the increment of the frequency change in the measuring system. The incremental error in the resonant frequency measurement was 0.12 MHz and the error in the transmission coefficient measurement, $\delta S_2$, was evaluated experimentally as 0.02 dB. These values introduced into Eqs. 17 and 18, together with average values for $\Delta F = 60$ MHz, $\Delta T = 2.3$, and $n_1 = n_2 = 3$, give the uncertainty in the moisture content measurement resulting from the measuring system instability, $\sigma_M = 0.294\%$ moisture. This value is smaller than the value of 0.79\% determined as the standard deviation of the verification experiments.

The uncertainty of kernel mass determination as calculated from Eqs. 16 and 18 for $n_1 = 3$ and $n_2 = 3$, is approximately 0.65 mg. This value is smaller than the value of 0.98 mg found experimentally. These indicate that the uncertainty in the weighing of a single kernel (average mass ~ 30 mg), ± 0.05 mg, has a negligible effect on the final accuracy of measurement. Thus, the mass of a single wheat kernel may be
Fig. 10. Distribution of differences between oven moisture content and moisture content calculated from the calibration Eq. 12 for 534 wheat kernels.

determined nondestructively with an uncertainty of 2 mg at the 95-percent confidence level.

An expression for the uncertainty in the moisture content determination by the reference method can be obtained by differentiation of Eq. 1 which is the definition of the moisture content determined on the wet basis. The expression has the form:

$$\sigma_c = \frac{100}{m_m} (m_m \Delta m_m + m_d \Delta m_d) = \frac{100 \Delta m}{m_m} (m_m + m_d)$$ (19)

where $\Delta m_m$ and $\Delta m_d$ denote errors in weighing the moist and dry kernel, respectively. The uncertainty $\sigma_c$ for $\Delta m_m = \Delta m_d = \Delta m = 0.05 \text{ mg}$ ranges from 0.24 to 0.29 % moisture for large and small wheat kernels, respectively.

**DISCUSSION AND CONCLUSIONS**

The microwave resonant cavity technique has proven to be a useful tool for moisture content determination in single grain kernels and seeds. The expected uncertainty in moisture content determination using the calibration equation developed, in the range of practical interest, can be less than 1.6 percent moisture, while the uncertainty in the kernel mass determination is less than 2 mg, both at the 95% confidence level. The measuring circuit can be simple and requires only commercially available devices. Changes in resonant frequency and the transmission coefficient of the cavity when loaded with a grain kernel are the only measured values. Thus, long-term stability of the measuring system is not required, because checking of the reference values for an empty cavity may be performed as often as necessary. Absolute values of either of these parameters are of no interest in routine measurements.

The measurement uncertainties resulting from the system instability and repeatability errors for moisture content and mass of the individual wheat kernels are much smaller than standard deviations determined experimentally during the verification procedure. Therefore, there must be another factor contributing to the spread in the experimental data. This factor could be a model error related to inability of the calibration equation in representing the effect of all physical characteristics of kernels upon the measured variables. One such characteristic may be kernel shape which varies significantly, even within samples from one lot. To verify the effect of kernel shape on measured variables, numerical examples were calculated from Eqs. 3 and 4 for kernels of the same moisture content (assuming identical kernel densities and values of permittivity) and different shape factors, determined by the kernel length/diameter ratio. For wheat kernels of $M = 16.8\%$ and $\varepsilon^* = 5.4 - j 0.86$ (Nelson and You 1989), the moisture content predicted from the calibration Eq. 12 changes by 1% for a length/diameter ratio varying from 1.85 to 2.62, which corresponds to the range observed for the verification data set. The effect of the kernel shape factor on predicted values of moisture content for particular values of kernel permittivities is shown in Fig. 12.

It may be noted from Fig. 8 that the accuracy of moisture content prediction for single wheat kernels is lower for very dry kernels. This may be a result of developing the calibration equation for moisture content with too few dry kernels and the verification being performed for a wider moisture content range using more dry kernels. It may be noted also from Fig. 7 that the slope of the transmission factor changes for small very dry kernels (mass of water lower than approximately 2.5 mg, which for kernels of 20-mg dry mass corresponds to a moisture content of 9%), and ultimately the relationship reaches zero for all bone dry wheat kernels. This change of slope is not accounted for in Eq. 10 and consequently in the calibration Eq. 12. However, the distribution of differences between measured and predicted moisture con-
sents has an apparently normal distribution (Fig 10). This suggests a random character of measurement error, which implies that the linear approximation of small losses in dry kernels has a small effect on the error distribution in the whole moisture content range of interest.

As mentioned, the discrete character of the measurement creates values of resonant frequency and transmission coefficient differing from their “true” values by \( n_1 \delta f \) and \( n_2 \delta \xi \), respectively. That in turn gives discrete values of moisture content calculated from the calibration equation that differ by \( nAX \) from the “real” value. If a set of such quantized values is subtracted from a uniformly distributed set of moisture content values determined by the reference method, the discrete character of differences may become obvious, as long as the number of samples (kernels) remains low in a statistical sense. The fact that uncertainty in moisture content prediction is higher for nonuniformly shaped wheat kernels than for almost identically shaped soybean seeds (Kraszewski et al. 1989) may be related to the shape variations among the objects rather than to poorer accuracy of one measuring system compared to the other. However, each commodity was measured in a different cavity, of different resonant frequency and \( Q \)-factor, and those factors also have to be taken into consideration. More study on different commodities in similar cavities is needed before conclusive statements can be presented.

By applying the high sensitivity of microwave resonant sensors, a fast, accurate, and nondestructive method of moisture content determination has been developed for grain kernels and seeds. Accuracies of 1.6% moisture content and 2 mg in mass may be obtained for individual wheat kernels without need for contact between these objects and the measuring system, thus providing an effective tool for determining the distribution of moisture content among kernels and detecting mixed lots of grain of different moisture levels.

REFERENCES


