Moisture Content Estimation in Paper Pulp Using Fringing Field Impedance Spectroscopy

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***Abstract*—Currently used methods for estimation of moisture content in paper pulp are restricted to levels of moisture concentration below 90%. Some of the existing methods require less practical double-sided contact measurements. A few other methods make restrictive assumptions, such as the constituents of the pulp that determine its conductance. This paper presents a technique that uses fringing field interdigital sensors to measure moisture concentration in paper pulp at levels as high as 96%. The method proposed in this paper uses single-sided measurements, offers high sensitivity, and does not require special operating conditions. The accuracy of the proposed method is also demonstrated. The repeatability and reproducibility of the sensor measurements are also shown.**

***Index Terms*—Additives, dielectric spectroscopy, fringing electric field, moisture measurement, paper pulp.**

I. Introduction

PAPER MANUFACTURERS are looking for noninvasive, noncontact sensing technologies that can accurately measure the moisture content of paper pulp at the wet end of the paper machine. The knowledge of the moisture concentration of the paper pulp in the initial stages of manufacturing process (wet end) would facilitate inclusion of feed-forward control techniques that could reduce deviations from the desired paper quality, thus reducing waste. The moisture content of the paper pulp at the wet end ranges from 90% to 96%. This high concentration of moisture in the pulp makes it difficult to detect small concentration fluctuations with adequate resolution. Fringing field dielectric spectroscopy is a sensing technology that could be used to estimate the moisture content of the paper pulp at the wet end of a paper machine.

The methods currently used to measure moisture in paper pulp are mostly intrusive [1]–[3], or require certain special operating conditions. Several patents [4], [5] have proposed using an electromagnetic field perturbation sensor for measuring water concentration in the wet end of the paper machine. In these patents, it is assumed that all the water in the pulp is held by paper fibers and that all of electrical conductivity is due to water molecules alone. The concentration of paper fibers in the pulp is indirectly determined by measuring the conductivity of the pulp. The first assumption limits the measurements to high concentrations of fiber content. At higher moisture levels, the fiber is in suspension in water and hence the assumption is no longer valid. The conductivity of the pulp is also altered by the presence of additives such as titanium dioxide, alkalis, and clay. Hence, this method cannot be adapted for measuring moisture content in the pulp under realistic operating conditions.

Microwave techniques have been used to study the subsurface moisture since 1970s [1], [6], [7]. When the propagating electromagnetic wave has a frequency that is equal to the resonance frequency of the medium of propagation, stationary waves are created. Every medium has its own characteristic resonance frequency. Hence, in a multicomponent system, the system's resonance frequency is a function of the resonance frequency of the individual components and their mole fractions. This characteristic can be used to determine the composition of materials [1], [6].

Attenuation-based microwave techniques have been used to estimate the moisture content of paper pulp [1]. The attenuation factor of the signal at resonance and the frequency shift are used to estimate the moisture content. Fiber concentration as low as 0.6% has been measured, with a standard deviation of 0.03% [1]. However, this method cannot be used for on-line monitoring of fiber concentration, as it requires a closed cavity resonator. More over, the method is sensitive only to fiber concentrations from 0.06% to 1%. In a paper machine, such concentrations of pulp can be found only at the headstock, where the presence of metallic stirrers and the high entropy of the pulp can affect the accuracy of the method.

The methods suggested in [7], [8] require measuring attenuation of the material, which is difficult to obtain [9]. The difficulty is more pronounced with low attenuation materials as the attenuation measurements are easily influenced by multiple reflections [9].

Most microwave techniques need at least two different types of measurements, such as attenuation and phase [8], or attenuation and density of sample [9]. If these techniques were to be realized, they would require at least two instruments [9] to obtain two different parameters. This would increase the measurement complexity and the cost of the measurement system [9].

Electromagnetic interference from other sources of radiation can affect the accuracy of microwave techniques. The resonance frequency of pulp is around 2.6 GHz [1], which is close to the commonly used 2.4 GHz communication channels. As the communication signals at 2.4 GHz are random in nature, their effect on the measurements cannot be effectively compensated. Hence, all the microwave systems have to be electromagnetically shielded, thus rendering the open cavity measurement

Manuscript received September 11, 2003; revised November 15, 2003. This work was supported in part by the Center for Process Analytical Chemistry of the University of Washington, in part by an NSF CAREER Grant 0093716, and in part by the EEIC, NESBI, and McNealy Scholarships. The associate editor coordinating the review of this paper and approving it for publication was Prof. Thaddeus Roppel.

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Digital Object Identifier 10.1109/JSEN.2004.824230

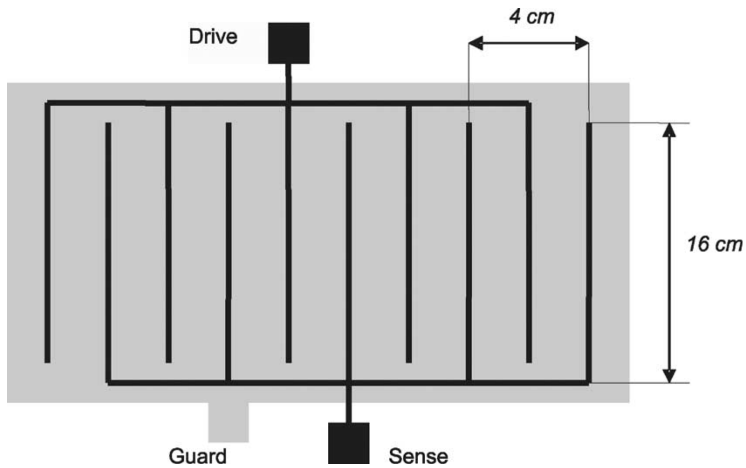

Fig. 1. Top-down view of the interdigital sensor tray with the spatial periodicity of 40 mm, finger length of 160 mm, and an approximate penetration depth of 13 mm.

models [6] impractical. The sensor reported in this paper uses a single-sided guard plane. The proximity of the guard plane to the sensing electrodes will ensure the immunity of the sensor to stray low frequency electromagnetic fields, especially the fields at 60 Hz as the sensor would also operate at frequencies well below 200 Hz. The stray fields will have to penetrate the pulp sheet and the wire to influence the sensor output. At the wet end, the paper pulp is spread on a semi-permeable membrane, known as the "wire," to aid the dewatering process. The authors believe that the stray field would have weakened sufficiently in the process of penetrating the pulp and the wire, and that the effect of it on the sensor output would be negligible.

II. Experimental Setup

The experiments reported in this paper emulate the operational conditions in a paper machine. The pulp in the wet end of the paper machine is primarily a suspension. This pulp suspension is spread on the wire and is, hence, unavailable for contact measurements. To emulate this setup in the laboratory, the pulp is blended to a consistency of a suspension and is placed on a tray. The tray wall prevents contact with the pulp, and hence is equivalent to the wire on the paper machine.

The sensor used for these measurements is an interdigital sensor tray with a spatial periodicity of 40 mm, finger length of 160 mm, and penetration depth of 7 mm. The sensor electrodes are not in direct contact with paper pulp. Instead, the sensor is attached to the outer side of the base of an acrylic tray with a wall thickness of 5 mm. A guard plane is placed underneath the sensor electrodes to provide shielding from external electric fields. The geometry of the sensor is shown in Fig. 1.

Measurements reported here were taken using the Fluke manufactured RCL meter (model PM 6304). It generates a one-volt sinusoidal AC voltage in the frequency range from 50 Hz to 100 kHz.

Known quantities of paper, water, and additives are mixed in a commercial blender to obtain the paper pulp. The pulp is then cooled to ambient temperature of 25 °C. The moisture loss due to evaporation can be neglected, as the loss is small compared to the total water content in the pulp. The prepared pulp is then deposited in the sensor tray. The homogeneity of spatial distribution of the pulp and reduction in the number of air pockets in the bulk of the pulp are achieved by manually rearranging the pulp in the tray.

The interdigital sensor tray filled with paper pulp is connected to the two channels of the RCL meter. The RCL meter calculates the effective impedance between the two channels by computing the magnitude attenuation and phase shift between the input voltage and loop current.

The measurements are made at frequencies in the range of 200 Hz to 100 kHz. The measurements made at the lower end of the frequency spectrum (below 200 Hz) have noise due to the ac power supply. The instrumentation limits the highest viable frequency to 100 kHz. Ten sets of measurements were taken at each frequency, and then averaged to reduce the noise. It is assumed that all sources of noise have zero mean distribution.

III. Experimental Results

Experiments were conducted to characterize the response of the sensor to the variation of moisture level in two-component pulp consisting of only water and fibers. The moisture content of the pulp was varied from 90% to 97% in steps of 1% and measurements were made using the setup described in Section II.

Fig. 2(a) shows the dependence of admittance on the moisture content and frequency. The variation in admittance with moisture content is not well pronounced.

Fig. 2(b) shows the dependence of phase on the moisture content and frequency. There are cross overs in the phase plots at various frequencies and moisture levels. This is partly due to instrumentation errors and also due to the fact that the phase is highly sensitive to noise. Hence, the phase shifts at two frequencies cannot be used with the frequency range under consideration to estimate the moisture content of the pulp as suggested in [9].

Fig. 2(c) shows the dependence capacitance on the moisture content and excitation frequency. It can be seen that the variation is monotonous and strictly decreasing with frequency and moisture content. As seen from Fig. 3, the obtained curves were found to be displaced by at least twice the standard deviation. Hence inaccuracies in measurement introduce relatively smaller errors in the concentration estimates.

Fig. 2(d) shows the dependence of conductance on the moisture content and excitation frequency. The spatial separation of

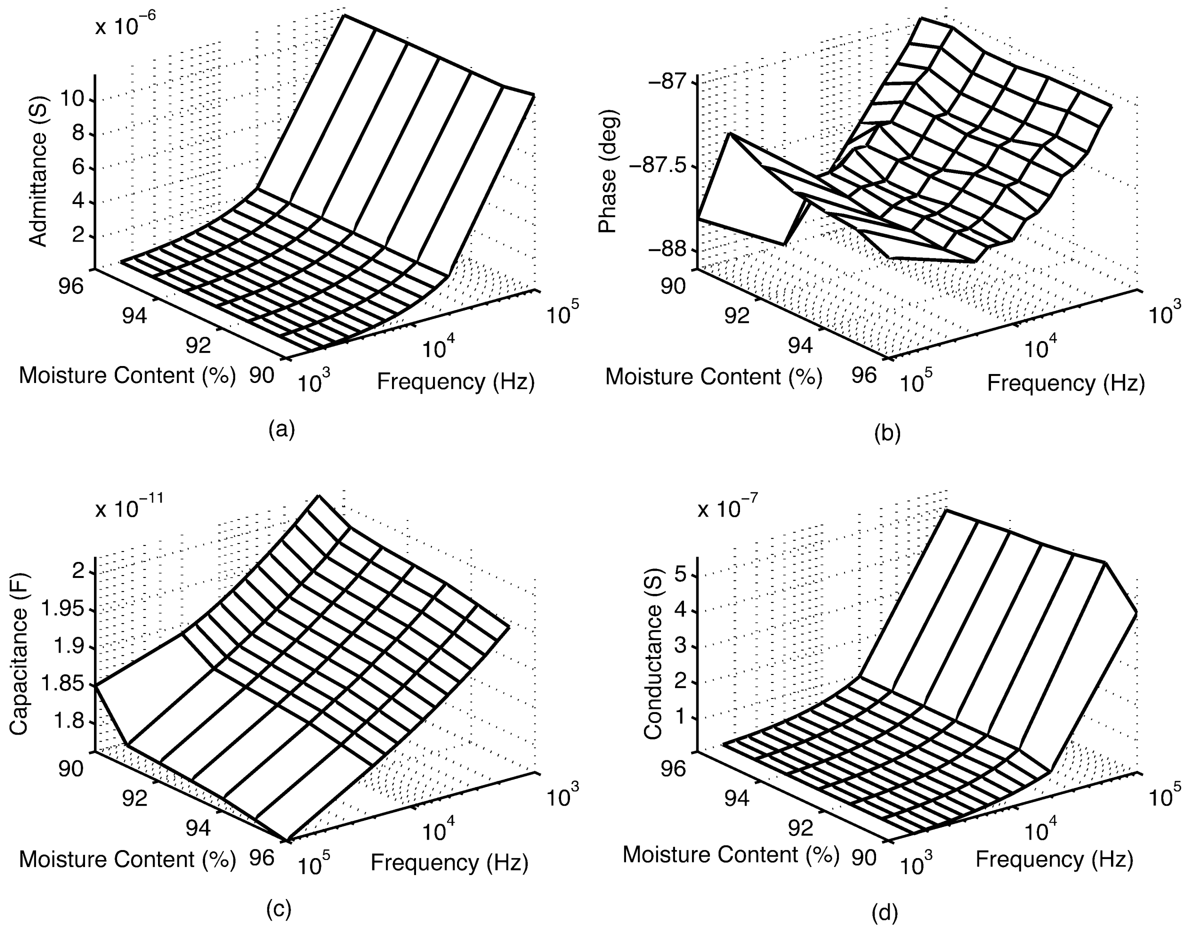

Fig. 2. Measurements of paper pulp samples with 90% to 97% moisture concentration at frequencies from 200 Hz to 100 kHz.

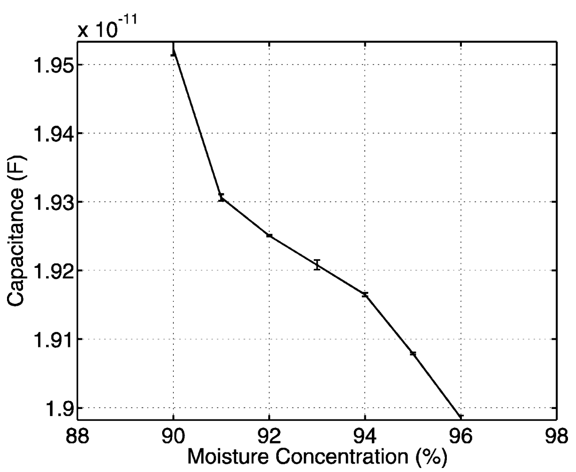

Fig. 3. Capacitance measured at 5 kHz shows separation between measurements to be much greater than twice the standard deviation. This indicates toward the possibility of achieving higher resolution using the sensor.

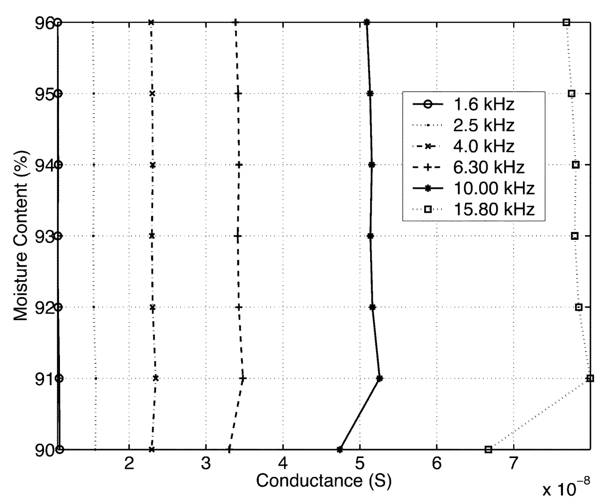

Fig. 4. Conductance plots from measurements of paper pulp samples with 90% to 96% moisture concentration at frequencies from 200 Hz to 100 kHz.

the curves is not adequate to mitigate the effect of any small inaccuracies in the measurement of conductance. This may explain the high error percentages reported in [3], [10], [11].

IV. Data Analysis

Fig. 4 shows the moisture content as a function of conductance at different frequencies. It can be seen that the rate of change of conductance with moisture content is small. Hence, it is not advisable to estimate the moisture content based on the conductance and the excitation frequency. This may be the main reason the methods suggested in [3]–[5], [19] did not perform adequately for lower fiber concentrations. The slopes of the curves are better defined at higher concentrations of paper

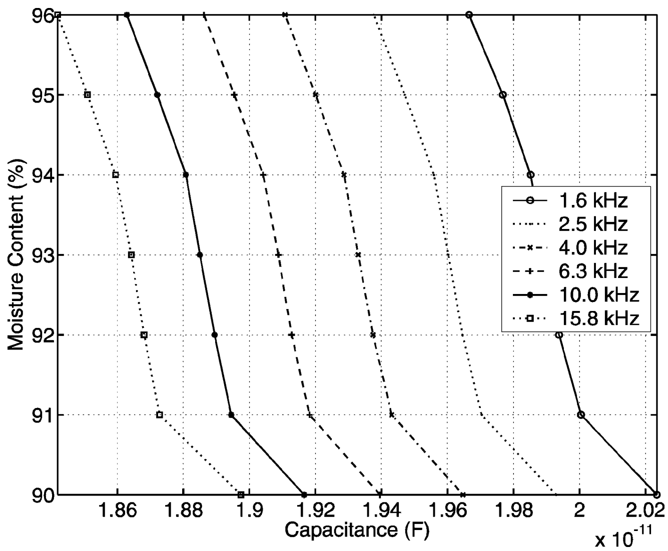

Fig. 5. Capacitance plots from measurements of paper pulp samples with 90% to 96% moisture concentration at frequencies from 200 Hz to 100 kHz.

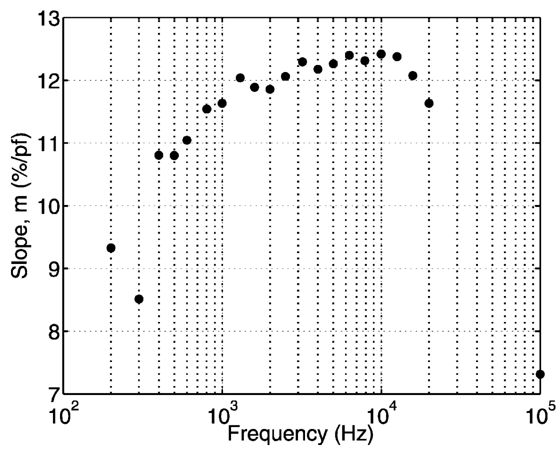

Fig. 6. Variation of the slope m in (1) depicting the plot between percentage of moisture content and capacitance with respect to frequency of excitation.

fiber, and hence the foresaid methods can be used to estimate the moisture content in those regions.

Fig. 5 shows the moisture concentration as a function of capacitance at different frequencies. It can be seen that slopes of the curves are higher than those of the conductance plots in Fig. 4. Hence, we estimate the moisture content of the pulp based on the measured capacitance measured and the frequency used.

The curves in Fig. 5 can be linearized and the relationship between moisture concentration, P and the capacitance C can be expressed as

$$P = m \cdot C + P_o \tag{1}$$

where m is the slope of the line and P_o is the offset constant. It can be seen that both m and P_o are related to the frequency of excitation.

Figs. 6 and 7, respectively, show the variation m and P_o with the excitation frequency. It can be observed that the resolution of this method is noticeably higher at lower frequencies and, hence, these frequencies offer smaller error margins.

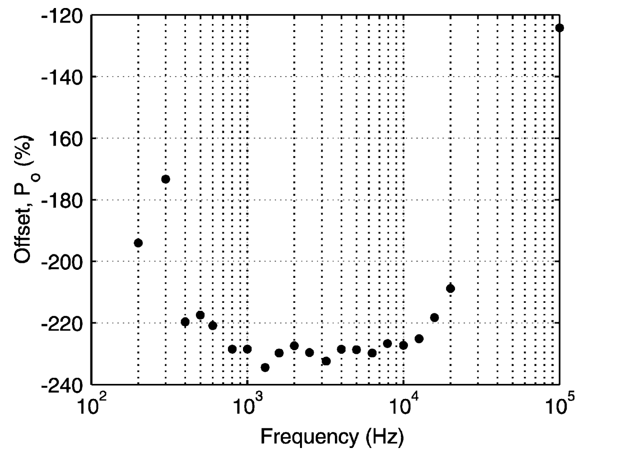

Fig. 7. Variation of the offset, P_o, in (1) depicting the plot between percentage of moisture content and capacitance with respect to frequency of excitation.

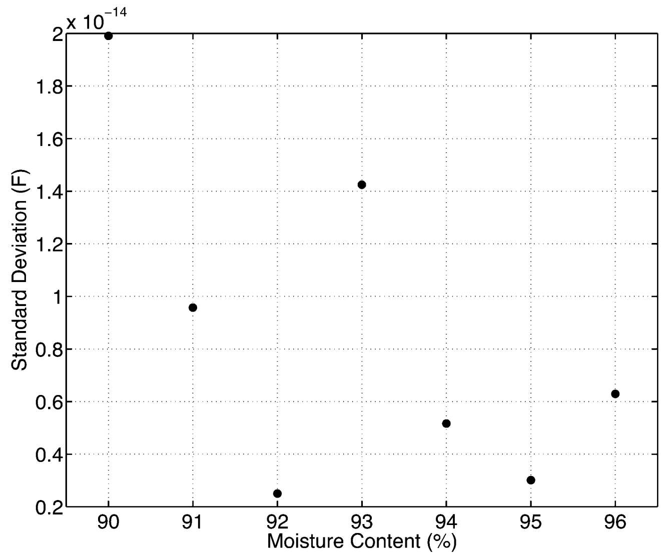

Fig. 8. Standard deviation of the capacitance measurements at various moisture levels is two orders of magnitude smaller than the capacitance (10^{-11} versus 10^{-14}).

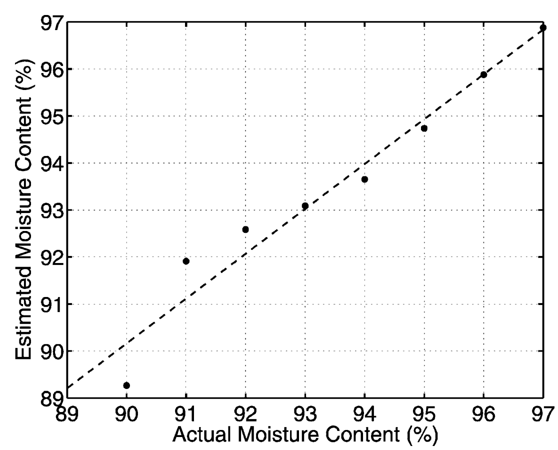

Fig. 9. Data obtained experimentally at 5 kHz is in agreement with the curve formulated in (1).

To determine the moisture content in the pulp given the capacitance of the pulp and the frequency of excitation used, we first

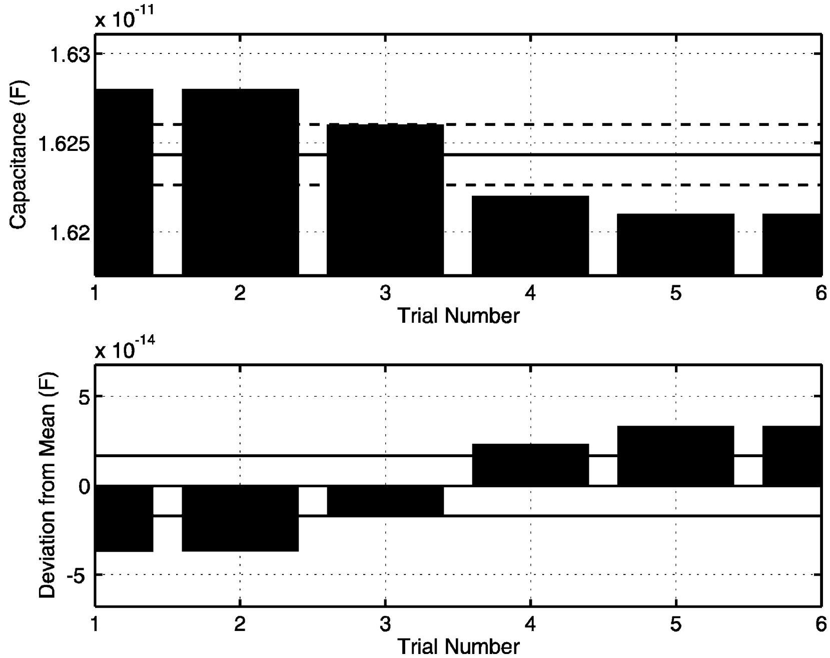

Fig. 10. Repeatability test for measurements made using pulp containing just fiber and water. The standard deviation is three orders of magnitude lesser than the mean.

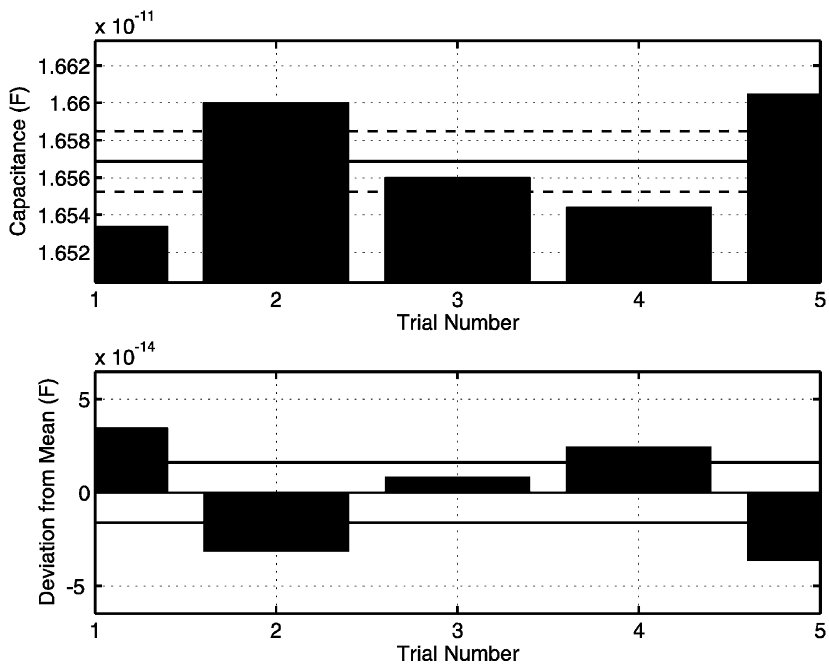

Fig. 11. Reproducibility test for measurements made using pulp containing just fiber and water. The standard deviation of the measured capacitance is three orders of magnitude lesser than the mean.

determine the corresponding values of m and P_o from Figs. 6 and 7. Once these values have been determined, they are substituted in (1) along with the measured capacitance and the moisture concentration is estimated.

The accuracy of this method relies on the ability to measure capacitance accurately and the sensitivity of the method. Fig. 8 shows the standard deviation of the measured capacitance at 5 kHz for various moisture concentration levels. It can be seen from Figs. 6 and 8 that the maximum standard deviation of the estimated moisture content would be approximately 0.2379%. Fig. 9 shows the conformity of the curve formulated in (1) to the data obtained experimentally.

V. Repeatability and Reproducibility Tests

The curve formulated in (1) will always be valid for estimation of moisture content for all similar pulp samples if adequate reproducibility is ensured. The ability of the sensor to repeat measurements is critical for estimation process.

A. Repeatability Test

The prepared pulp sample was placed in the sensor and measurements were made. The measurements are repeated approximately every 3.24 s. During this process, neither the sensor, nor the pulp, is disturbed.

The sample had 90% moisture content with 10% fiber. Six sets of measurements were made. Fig. 10 shows the results of the repeatability test for capacitance measured at 7.9 kHz. The mean capacitance was 16.24 pF. The standard deviation was found to be 0.033 86 pF, three orders of magnitude smaller than the mean. The estimated moisture concentration showed a peak-to-peak variation of 0.866 73%.

B. Reproducibility Test

The ability of the sensor to reproduce the measurements for similar pulp sample is established by the reproducibility test. The prepared pulp sample was placed in the sensor and measurements were made. The pulp sample is then removed from the sensor. The sensor surface is cleaned and then the same pulp sample is deposited back into the sensor tray.

The reproducibility tests were performed on two types of pulp samples. The first sample had 90% moisture content with 10% fiber. Five sets of measurements were made. Fig. 11 shows the results of the reproducibility test for the estimated moisture content, based on capacitance measured at 4 kHz.

The mean capacitance measured was 16.569 pF. The standard deviation was found to be 32.354 fF, three orders of magnitude lesser than the mean. The peak-to-peak variation in the estimated moisture content was found to be 0.880 33%.

VI. CONCLUSION

The ability of the fringing electric field sensing method to accurately measure the moisture content in paper pulp has been demonstrated. The sensor's repeatability and reproducibility have been experimentally verified. Immediate future work will focus on the effect of additives, temperature, and pass-line sensitivity.

ACKNOWLEDGMENT

The authors would like to thank Dr. M. Munidasa, for his valuable guidance and input, and the undergraduate students A. Zyuzin, N. Semenyuk, and C. Wai-Mak, for their assistance with experimental aspects of this work.

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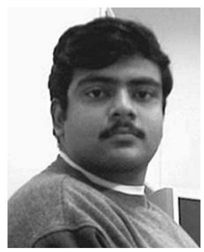

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