Measuring moisture, fiber, and titanium dioxide in pulp with impedance spectroscopy

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ABSTRACT: In a new measurement technique, impedance spectroscopy is used with fringing electric field sensors to measure the concentration of moisture, fiber, and titanium dioxide in pulp. This method can be integrated into a paper machine without disrupting the manufacturing process because the measurements are taken without contacting the pulp. Experimental results show consistent accuracy is when the moisture concentration is from 94% to 86% and the concentration of other constituents in the pulp is between 0% and 7%. The calibration procedure can be implemented with only a few experimental data points.

Application: By accurately measuring the pulp moisture at the wet end of the paper machine, papermakers can exercise more precise control over the early stages of paper production.

The papermaking industry is moving towards greater energy efficiency and reduced material waste, as outlined in the FA&PA Agenda 2020 initiative [1–3]. Novel sensor technologies, coupled with adaptive process control, will help make manufacturing more efficient. One of the promising areas of improvement is the measurement of the moisture content of pulp at the wet end of the paper machine with noncontact, noninvasive sensors. Here, we present a technique for making such a measurement with a fringing electric field sensor.

BACKGROUND

In papermaking, the moisture content of the pulp is gradually reduced from concentrations as high as 98% to about 6%. The process of dewatering is first carried out in the wet end by aerofoils and then in the heating section by steam-heated rollers. If the moisture content of the pulp can be measured at the wet end, this information can be sent to the aerofoil controllers downstream. These controllers can then compensate for deviations from the setpoint by adjusting the angle of the aerofoils. This approach would be a cost-effective way to control moisture.

The fiber content of the pulp at the wet end ranges from 1% to 30%. This low concentration of fiber makes it hard to detect concentration fluctuations with adequate resolution. Microwave techniques [4–8], electromagnetic field perturbation [9, 10], infrared scanning [11], and parallel-plate impedance sensing [12] have been used to measure moisture in pulp. Among these techniques, reviewed in detail elsewhere [13], no single one is so satisfactory that it has become dominant.

One of the main difficulties is the need to measure several components accurately at the same time. The pulp at the wet end contains high quantities of chemical additives [14]. Since most methods currently used for measuring moisture do not allow for the presence of additives, they are not entirely suitable for monitoring the moisture of the pulp in a paper machine.

In this study, we examine fringing field impedance spectroscopy as a sensing technology that could be used to estimate the moisture content of the pulp at the wet end [15]. This method can measure the percentage composition of the constituents of the pulp in the presence of additives. Here, the filler we focus on is titanium dioxide, one of the commonly used additives [14, 16–18]. Titanium dioxide is used as a whitening agent in common paper and is sometimes used as filler in paper of very high quality.

INTERDIGITAL FRINGING FIELD SENSORS

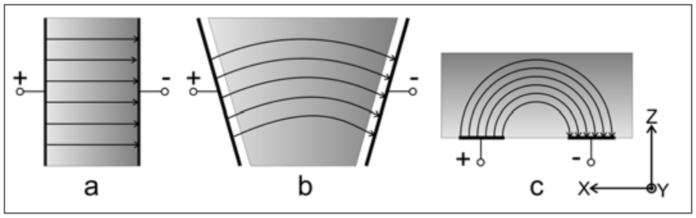
The interdigital fringing field sensor operates much like a conventional parallel-plate capacitor works. **Figure 1** shows the transition from a parallel-plate capacitor to a fringing field sensor. The electric field lines always penetrate the bulk of the material under test, irrespective of the position of the electrodes. The material geometry also determines the effective length to which each field line penetrates the material. Hence, in addition to the electrode geometry, capacitance between the electrodes also depends on the material dielectric properties and material geometry.

As seen in the third illustration in the figure, the electrodes of a fringing field sensor are coplanar. In a coplanar electrode configuration, the field lines have to travel further and are likely to encounter more disturbance than the field lines of a parallel plate configuration. The signal-to-noise ratio of measured capacitance of the sensor in Fig. 1c can be very low unless the electrode pattern is repeated several times.

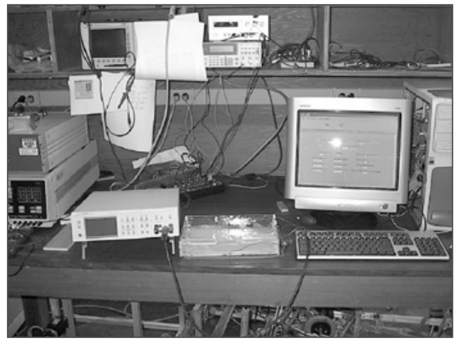
When the pattern is repeated, the resulting structure is known as an "interdigital" structure. The term refers to a digit-like or finger-like periodic pattern of parallel, in-plane electrodes. These electrodes build up the capacitance associated with the electric fields that penetrate a material sample [19].

In an interdigital sensor, the spatial wavelength of the sensor, λ, is defined as the distance between the centers of two adjacent electrodes of the same type. For a semi-infinite, homogeneous medium placed on the surface of the sensor, the electric potential along the x axis varies periodically. This variation creates an exponentially decaying electric field that penetrates the medium along the z axis.

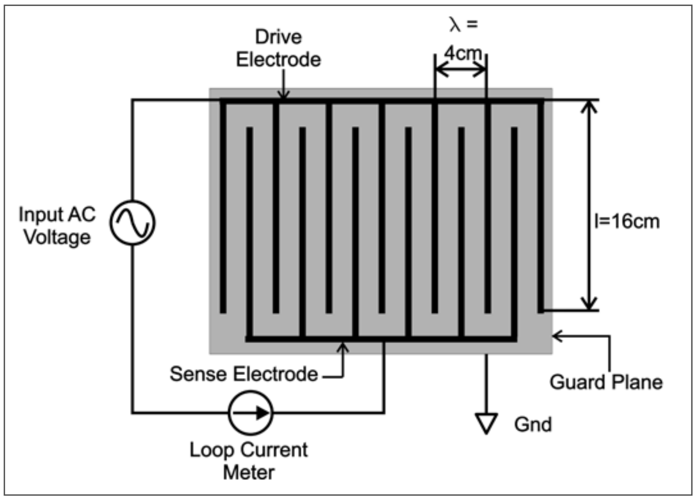
Variations in the shade of the material in Figure 1 indicates that there are probably z-axis variations in the material's properties. The model for analyzing such multilayered systems is discussed in detail elsewhere [19, 20]. A thorough description of design, manufacturing, modeling, and applications of the interdigital sensors can also be found elsewhere as well [20].



1. A fringing field dielectrometry sensor can be visualized as a parallel plate capacitor (a) with electrodes that open (b) to provide one-sided access (c) to the material being tested.



2. Photograph of the experimental setup.



3. Top-down view of the interdigital sensor tray.

Sample no.	TiO_2, %	Moisture, %	Fiber, %
1	0	93.00	7.00
2	1	92.07	6.93
3	2	91.14	6.86
4	3	90.21	6.79
5	4	89.28	6.72
6	5	88.35	6.65
7	6	87.42	6.58
8	7	86.49	6.51

I. Composition of the pulp samples.

EXPERIMENTAL SETUP

The experiments were designed to emulate the operating conditions in a paper machine. In the wet end, the pulp is prepared so that the fibers form a homogeneous suspension in water. The moisture content of the pulp is above 98% at this stage of the manufacturing process. The pulp loses most of its moisture on the wire as a result of the vibrations from the rollers and the pressure differential caused by the aerofoils. By the end of the wire section, the pulp forms a paper web with a moisture content of about 70%. Our purpose was to measure the moisture content of the pulp while it is on the wire.

Figure 2 is a photograph of the experimental setup. The pulp was placed in the acrylic tray, and the sensor was placed beneath it. The sensor used was an interdigital sensor with a spatial periodicity of 40 mm, a finger length of 160 mm, and a penetration depth of 7 mm. A guard plane was placed underneath the sensor electrodes to shield it from external electric fields.

Measured quantities of paper fiber, titanium dioxide, and water were mixed in a commercial blender. The pulp was cooled to 25°C and placed in the sensor tray. The geometry of the sensor and the electrical connections are shown in **Fig. 3**.

The RCL meter generates 1 volt sinusoidal AC voltage in the frequency range of 50 Hz to 100 kHz. At each frequency, the meter calculates the effective impedance between the two channels by computing the magnitude of attenuation and phase shift between the input voltage and the loop current. This general-purpose instrument is good for studying the relative effects of different additives. In the future, this type of measurement could be made with multi-channel, custom-built circuits to gather data at more than one measurement point.

The measurements were made at frequencies in the range of 200 Hz to 100 kHz. Ten sets of measurements were taken at each frequency and were averaged to reduce the noise. All sources of noise were assumed to have zero mean distribution.

EXPERIMENTAL RESULTS

Experiments were conducted to characterize the response of the sensor to the variation in moisture in a pulp consisting of water, titanium dioxide, and fiber. The titanium dioxide content of the pulp was varied from 0% to 7% in steps of 1%, and the moisture content was varied from 94% to 86%, as shown in **Table I**.

Twenty-one electrical parameters, not all of which were independent, were measured or derived from measurements for each pulp sample at every frequency. Here, we consider only four parameters—the capacitance, the magnitude of complex admittance, the conductance, and the phase.

Figure 4 shows the seven-dimensional scatter plot of the measurements of pulp samples with 0–7% TiO_2 at 100 kHz. The plot shows the variation of electrical parameters such as capacitance, admittance, conductance, and phase. It also shows the percentage concentrations of titanium dioxide, moisture, and fiber in the pulp with respect to each other. Each of these parameters is plotted against every other parameter in one of the rows of the scatter plot. For example, the first row shows the variation of capacitance against admittance, phase, conductance, and the percentage composition of the constituents of the pulp.

The main advantage of representing the data this way is that the underlying correlations among measured parameters become explicit, and data trends in the experiment become more apparent. For example, in the data shown in Fig. 4, the data points at 92% and 93% moisture content are noisy.

Figure 5 shows the five-dimensional scatter plot of the measurements of a pulp sample with 4% titanium dioxide, 89.28% moisture, and 6.72% fiber concentration at frequencies from 900 Hz to 100 kHz.

The scatter plots in row and column (4, 5), (4, 6), and (4, 7) of Fig. 4 and (4, 5) of Fig. 5 show the dependence of conductance on the titanium dioxide concentration, the moisture content, the fiber content, and the frequency. The spatial separation of the curves is not adequate to mitigate the effect of any small inaccuracies in the measurement of conductance, which may explain the high measurement uncertainties reported in other research [21–23].

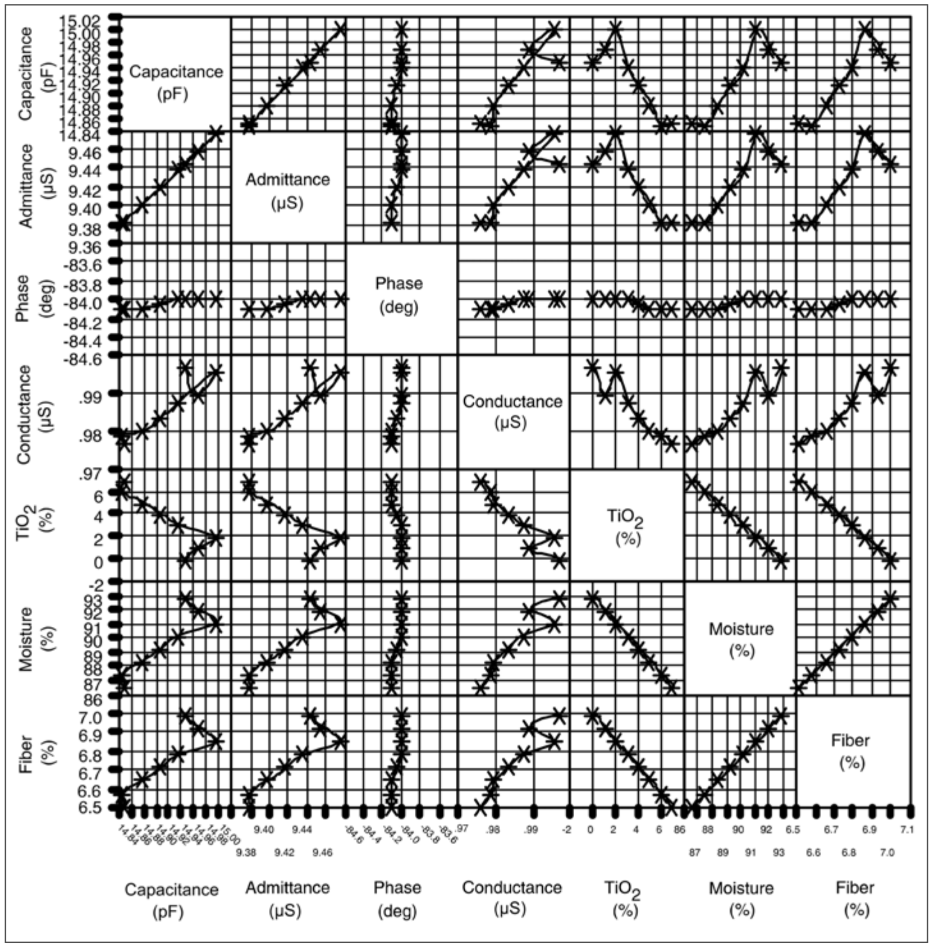
The scatter plots in (3, 5), (3, 6), and (3, 7) of Fig. 4 and (3, 5) of Fig. 5 show that the variation of phase is minimal with respect to the percentage composition of the constituents of the pulp. Therefore, the phase shifts at two frequencies cannot be used with the frequency range of 900 Hz to 100 kHz to estimate the moisture content of the pulp, as suggested by others for microwave frequency measurements [8].

The scatter plots in Rows 1–4 of Fig. 4 show that the variations in capacitance, conductance, and other electrical parameters are influenced by all three components of the pulp. Since two independent variables are involved here, it is not possible to estimate the fiber concentration with a single parameter. Instead we use a linear model with three variables to solve for the percentage composition of the constituents of the pulp. The linear model is given by Eq. 1:

$$\begin{bmatrix} p \\ t \\ w \end{bmatrix} = \begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} + \begin{bmatrix} C_1 \\ C_2 \\ C_3 \end{bmatrix} \quad (1)$$

where fiber concentration p, titanium dioxide concentration t, and moisture content w are estimated using any three electrical parameters X, Y, and Z and constants $m_{11}, m_{12}, m_{13}, m_{33}$ and C_1, C_2, and C_3. The key to the success of the estimation is in the choice of the parameters X, Y, and Z, the constants m_{11}, m_{12}, m_{13}, and m_{33}, and the constants C_1, C_2, and C_3.

To select the best possible set of parameters and constants, we first form a list of all possible sets of parameters. For each set, by using Eq. 1 along with the measured values and the values of the pulp composition from the training data set, we estimate the constants m_{11}, m_{12}, m_{13}, and m_{33} and the constants C_1, C_2, and C_3 by a least squares fit algorithm. We then substitute these constants and the measured electrical parameters into Eq. 1 and estimate the percentage content of fiber, moisture, and titanium dioxide in the pulp.



4. Measurements of pulp samples with 0–7% titanium dioxide concentration at 100 kHz.

Since the exact composition is already known, the estimation error for each pulp component can be calculated. The parameters and their estimation errors are tabulated, and the process is repeated for all possible combinations of the parameter set. Finally, the parameter set that produces the least estimation error is chosen.

In **Fig. 6**, the calculated concentrations of fiber, titanium dioxide, and moisture are compared with the measured concentrations. The estimates were based on the measured phase, capacitance, and conductance.

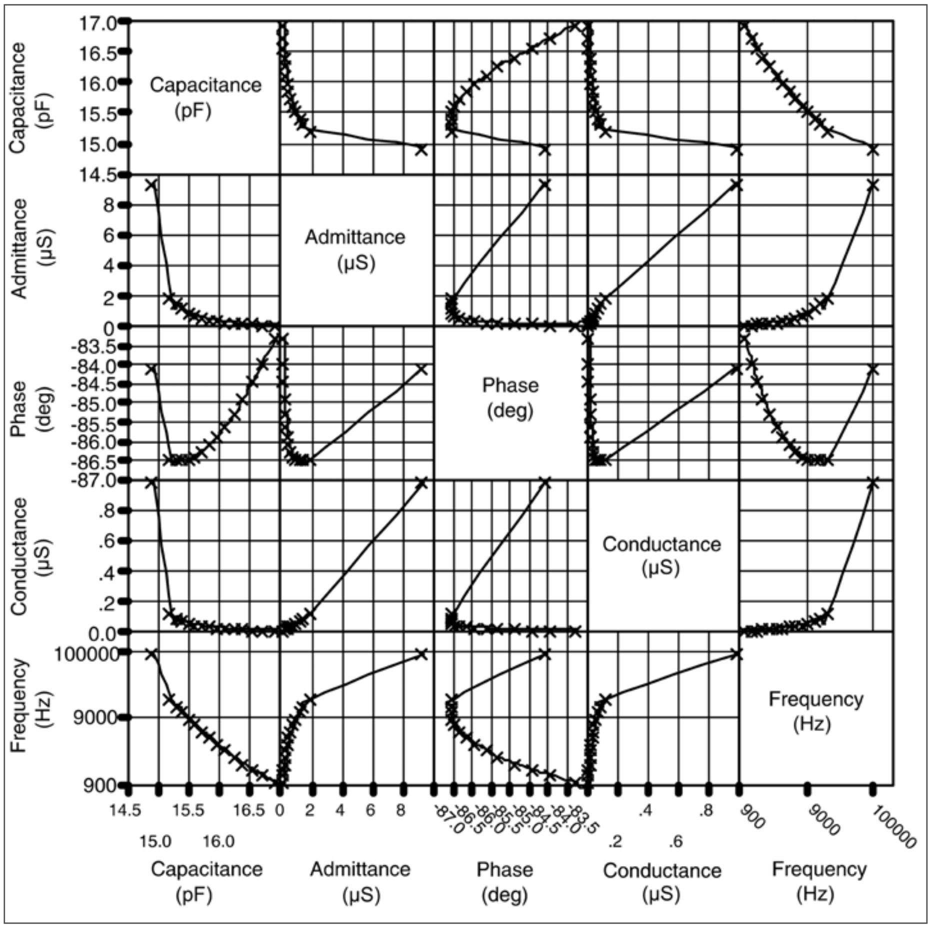
BLIND DATA TESTS

To validate the estimation algorithms, we conducted blind data tests. The algorithm was trained with data from a single experiment. One of the data points was omitted in the training data set; this omitted point served as a blind data point. The entire data from the experiment were then provided to the estimation algorithms, and the estimated moisture content was compared to the actual moisture content.

Figure 7 shows the results of the validation tests. These tests demonstrate the method's ability to estimate the percentage composition of the constituents of the pulp at points that are not included in the training data set.

CONCLUSIONS AND FUTURE WORK

The sensing technique can accurately measure the moisture content in pulp in the presence of titanium dioxide. The method relies on a small number of preliminary measurements. Through a multivariable training procedure, the property estimation algorithms are trained to select the combinations of measured electrical variables that respond to the



5. Measurements of pulp sample with 4% titanium dioxide, 89.28% moisture, and 6.72% fiber concentration at frequencies ranging from 900 Hz to 100 kHz.

observed combination of process parameters in the most unambiguous way.

Chemometric tools, such as principle component analysis with partial least squares fit, represent the next step. These tools will be used to extract variables that are purely functions of the percentage composition of the constituents of the pulp under study. The electrical measurements are influenced by fluctuations in the temperature of the pulp, the ambient temperature, and the distance between the pulp and the sensor electrodes. The effects of these fluctuations, which are also being studied, will be accounted for in the next generation of property estimation algorithms. **TJ**

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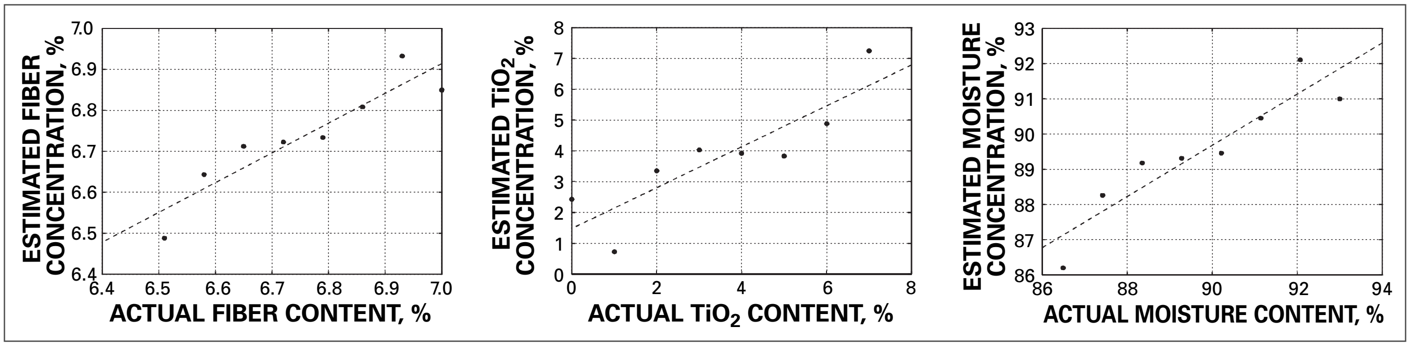
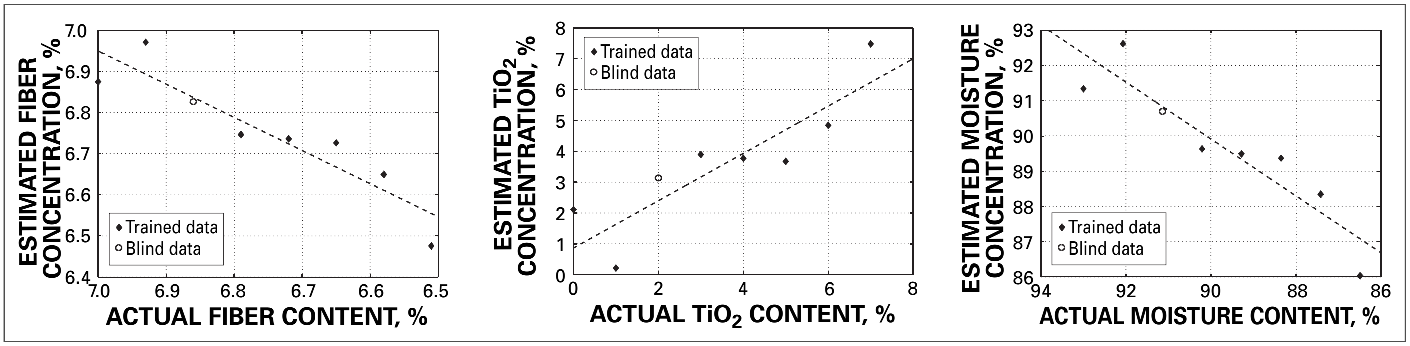


6. Estimated vs. actual concentration for fiber, titanium dioxide, and moisture in the pulp.



7. Validation of estimations of fiber concentrations, titanium dioxide, and moisture with one data point selected as a blind test in each set.

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