# Estimation of Moisture Content in Paper Pulp Containing Calcium Carbonate Using Fringing Field Impedance Spectroscopy

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## I. ABSTRACT

Currently used methods for estimation of moisture content in paper pulp are restricted to levels of moisture concentration under 90%, and also assume that there are no additives in the pulp. This paper presents a technique that uses fringing field interdigital sensors to measure moisture concentration in paper pulp in the presence of calcium carbonate. The method proposed in this paper uses single-sided measurements, offers high sensitivity, and does not require special operating conditions. A self-adapting algorithm used for data extraction is also introduced. The accuracy of the proposed method is also demonstrated.

## II. INTRODUCTION

Paper manufacturers are looking for non-invasive, non-contact sensing technologies that can accurately measure the fiber content of paper pulp at the wet end of the paper machine. The fiber content of the paper pulp at the wet end ranges from 1% to 30%. This low concentration of fiber in the pulp makes it hard to detect concentration fluctuations with adequate resolution. In addition to fiber and water, the paper pulp at the wet end contains high quantities of chemical additives [1]. 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 [2].

One of the most commonly used additives is calcium carbonate. It is used as whitening agent in common paper, and sometimes as filler in very high quality paper. References [3-9] discuss the uses of calcium carbonate in paper manufacturing in detail.

The methods currently used to measure moisture in paper pulp are mostly intrusive [10-12], or require certain special operating conditions. Several patents [13,14] have proposed using an electromagnetic field perturbation sensor for measuring the 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 altered by the presence of additives such as calcium carbonate, 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 [10,15,16]. 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 multi-component 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 [10,15].

Attenuation based microwave techniques have been used to estimate the moisture content of paper pulp [10]. 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 the standard deviation of 0.03% [10]. 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 [16,17] require measuring attenuation of the material, which is difficult to obtain [18]. The difficulty is more pronounced with low attenuation materials as the attenuation measurements are easily influenced by multiple reflections [18].

Most microwave techniques need at least two different types of measurements, such as attenuation and phase [17], or attenuation and density of sample [18]. If these techniques were to be realized, they would require at least two instruments [18] to obtain two different parameters. This would increase the measurement complexity and the cost of the measurement system [18].

Electromagnetic interference from other sources of radiation can affect the accuracy of microwave techniques.

The resonance frequency of pulp is around 2.6 GHz [10], 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 models [15] impractical. The sensor reported here in this report 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. The stray fields will have to penetrate the pulp sheet and the wire to influence the sensor output. The authors believe that the stray field would have weakened sufficiently in the process of penetrating the pulp and the wire, that the effect of it on the sensor output would be negligible.

## III. 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 to a semi-permeable membrane made of nylon or similar polymer, 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, calcium carbonate, and water are mixed in a commercial blender to obtain the paper pulp. The pulp is then cooled to the 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 then connected to the two channels of the RCL meter and measurements are made.

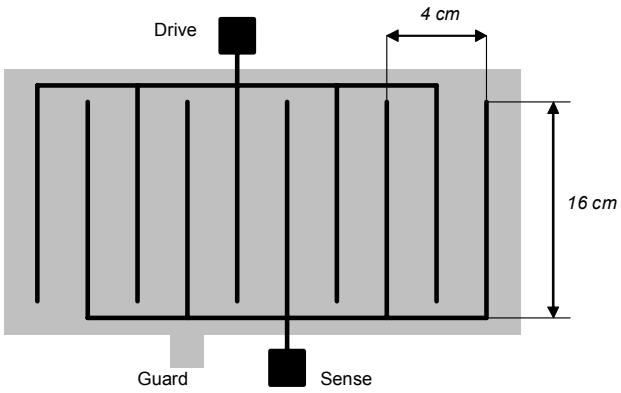


Fig. 1. The top-down view of the interdigital sensor tray with the spatial periodicity of 40 mm, finger length of 160 mm and an approximate penetration depth of 13 mm.

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.

## IV. EXPERIMENTAL RESULTS

Experiments were conducted to characterize the response of the sensor to the variation of moisture level in three-component pulp consisting of water, calcium carbonate, and fibers. The calcium carbonate content of the pulp was varied from 0% to 2.5% in steps of 0.5%, and the moisture content is maintained a constant at 90%, and measurements were made using the setup described in Section III.

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

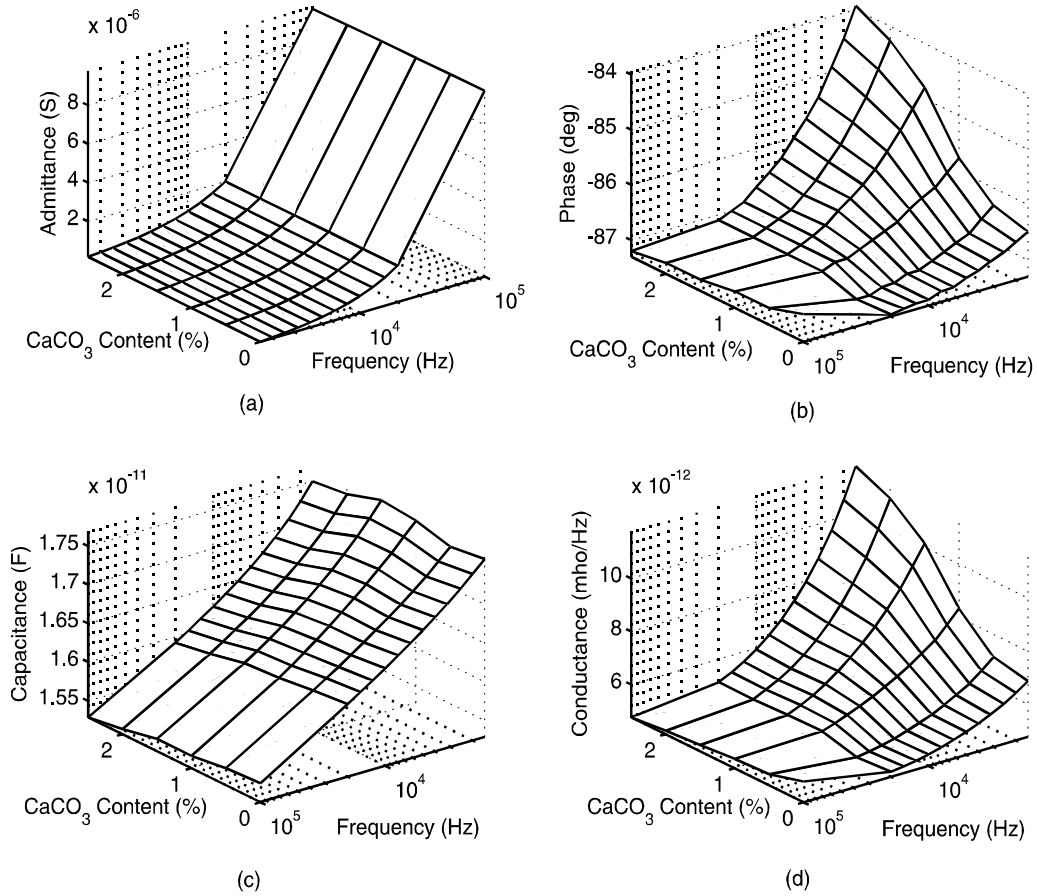


Fig. 2. Measurements of paper pulp samples with 10% to 7.5% fiber concentration and 0% to 2.5% calcium carbonate at frequencies from 200 Hz to 100 kHz.

Fig. 2(b) shows the dependence of phase on the calcium carbonate concentration, moisture content, and frequency. As the phase variation is usually noisy, 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 [18].

Fig. 2(c) shows the dependence of capacitance on the calcium carbonate concentration, moisture content, and excitation frequency. The change in capacitance with calcium carbonate content is negligibly small. This indicates that the reactance of the pulp is dominated by moisture concentration.

Fig. 2(d) shows the dependence of conductance on the calcium carbonate concentration, moisture content, and frequency. The conductance increases with the calcium carbonate content. This is due to the presence of free carrier ions in calcium carbonate, which increase the conduction of the pulp. The increase in conduction, with the capacitance remaining nearly the same is reflected in the change in phase.

## V. DATA ANALYSIS

The variations in capacitance, conductance, and other electrical parameters are influenced by all three components of the pulp, namely, paper fiber, calcium carbonate, and moisture. Since two independent variables are involved here, it is not possible to estimate the fiber concentration using a single parameter as in [19]. So we solve the inverse problem, by estimating any three of the electrical parameters as

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

where *X, Y* and *Z* are the electrical parameters estimated using fiber concentration *p*, calcium carbonate concentration *t*, moisture content *w,* and constants $m_{11}$, $m_{12}$, $m_{13}...m_{33}$ and $C_1$, $C_2$, and $C_3$.

Once the constants are determined, the parameters *X, Y* and *Z* can be used to estimate the concentrations of water, calcium carbonate, and fiber in the pulp using (2), (3), and (4) respectively.

$$w = \frac{e(\alpha - d) - a(\beta - g)}{eb - af} \quad (2)$$

$$t = \frac{f(\alpha - d) - b(\beta - g)}{af - be} \quad (3)$$

$$p = 100 - (t + w) \quad (4)$$

where,

$$a = \left(m_{12}m_{21} - m_{11}m_{22}\right) \quad (5)$$

$$b = \left(m_{12}m_{31} - m_{11}m_{32}\right) \quad (6)$$

$$d = \left(m_{12}c_1 - m_{11}c_2\right) \quad (7)$$

$$e = \left(m_{13}m_{22} - m_{12}m_{23}\right) \quad (8)$$

$$f = \left(m_{13}m_{32} - m_{12}m_{33}\right) \quad (9)$$

$$g = \left(m_{13}c_2 - m_{12}c_3\right) \quad (10)$$

$$\alpha = \left(m_{12}X - m_{11}Y\right) \quad (11)$$

$$\beta = \left(m_{23}Y - m_{22}Z\right) \quad (12)$$

The key to the success of the estimation is in the choice of the parameters *X*, *Y,* and *Z*, and the constants $m_{11}$, $m_{12}$, $m_{13}...m_{33}$, and $C_1$, $C_2$, *and* $C_3$.

Fig. 3, Fig. 4, and Fig. 5 respectively compare the concentrations of fiber, calcium carbonate, and moisture as obtained using the method described above. The estimates were based on the measured phase, capacitance and conductance. These parameters were chosen using the algorithm detailed in Section VI.

## VI. PARAMETER ESTIMATION ALGORITHM

Fig. 2 illustrates that all the electrical parameters measured are dependent on the moisture content of the paper pulp. Hence, there is a choice of parameters that can be used to estimate the moisture content. We propose an algorithm to choose these parameters.

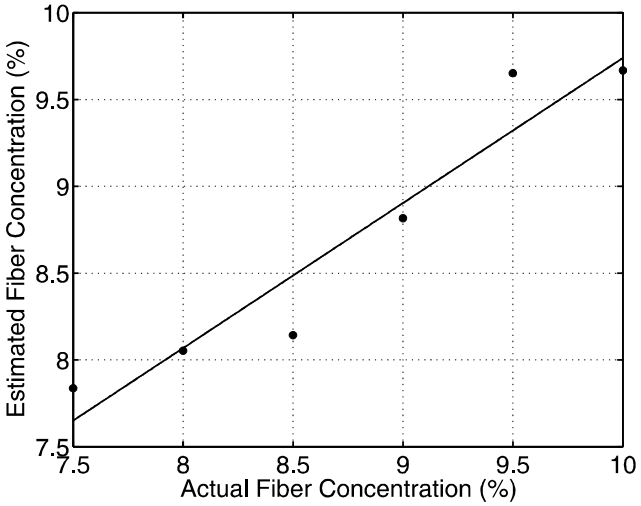


Fig. 3. Comparison of the estimated concentration of fiber in the pulp to the actual concentration.

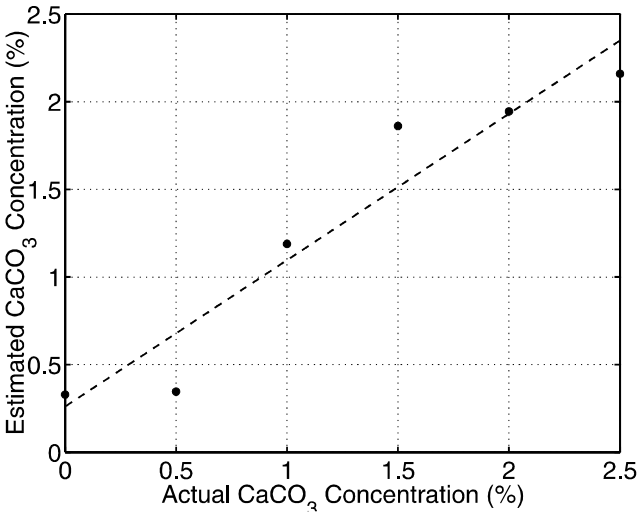


Fig. 4. Comparison of the estimated concentration of calcium carbonate in the pulp to the actual concentration.

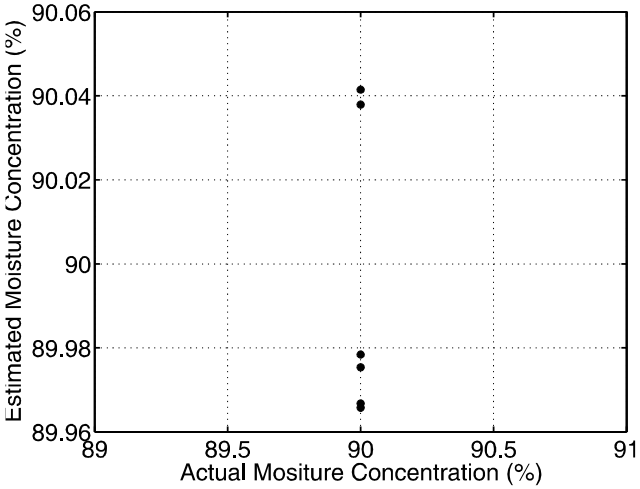


Fig. 5. Comparison of the estimated concentration of moisture in the pulp to the actual concentration.

Fig. 7 shows the flowchart for the training process. There are 12 basic electrical parameters that are measured or calculated over a frequency range of 500 Hz to 100 kHz for each of the paper pulp samples. These form the base parameters for the estimation process. Derived parameters are then obtained from a linear combination of any two of the base parameters. To exploit the spectral data in these parameters, parameters are further derived from a linear combination of the value of a parameter at two distinct frequencies.

Each of the base and the derived parameters are used to derive a linear estimation model similar to that shown in (1). Least square fitting technique is used to obtain these models. Based on the model obtained, the fiber concentration of the paper pulp is estimated for numerous training data sets. The mean estimation error is then calculated for all of the parameters for each of the data sets. The parameters are then ranked according to their accuracy

for each individual data set. The sum total of the ranks for the parameters is then calculated. The methods with the 10 highest total ranks are then compared with each other based on the product of their sensitivities and the accuracies to which they can be measured. The standard deviation of the parameters in the given training data set is used as a measure of measurement accuracy. This product is a measure of the inherent unbiased error component of the estimated fiber content.

Fig. 6 shows the flowchart for the estimation process. The parameter and the model selected during the training are used to estimate the moisture content of the given pulp sample. At the end of measurement, the data set collected during the estimation process is added to the database of the training set and the system is re-trained. This improves the accuracy of the method over time.

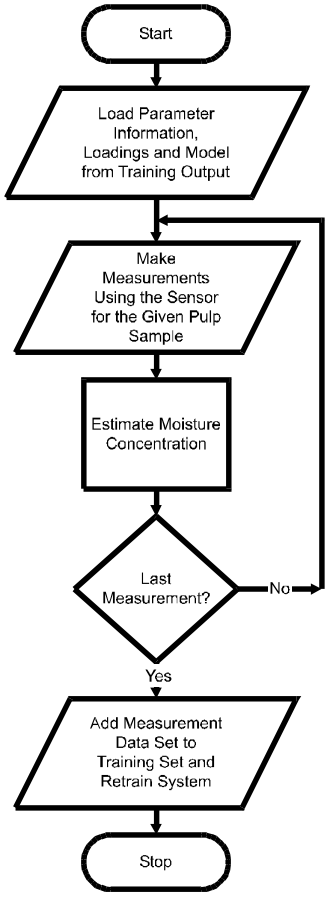


Fig. 6. Flow chart of the estimation algorithm.

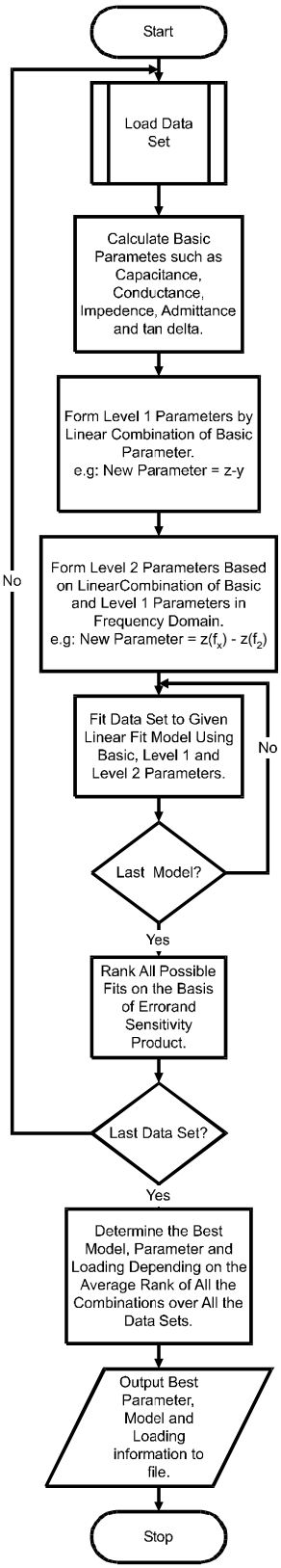


Fig. 7. Flow chart of the training algorithm.

## VII. BLIND TESTS

To validate the estimation algorithms presented in Section V, blind data tests were conducted. The algorithm was trained using the data from a single experiment. One of the data points obtained was omitted in the training data set. Hence, for the purpose of evaluation, the omitted data point serves as a blind data point. The entire data from the experiment is then provided to the estimation algorithms, and the estimated moisture content is compared to the actual moisture content. Fig. 8 shows the result of the validation tests performed.

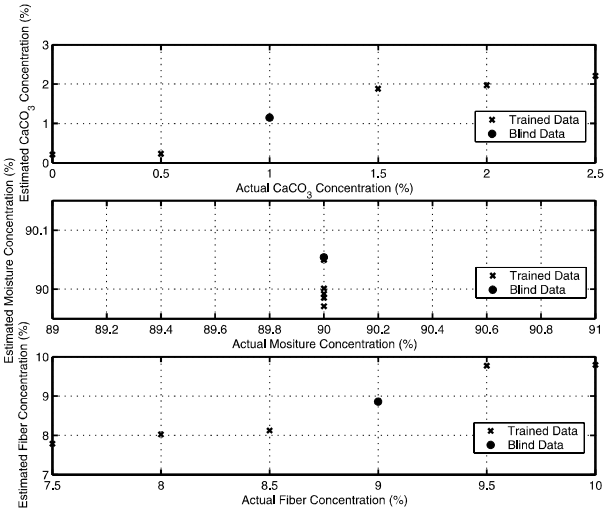


Fig. 8. Validation of estimation process described in Section-V.

## VIII. REPEATABILIY TEST

The ability of the sensor to repeat measurements is critical for estimation process. The prepared pulp sample was placed in the sensor and measurements were made. The measurements are repeated approximately every 3.24 seconds. During this process, neither the sensor, nor the pulp, is disturbed

The sample had 90% moisture content, 7.5% fiber, and 2.5% calcium carbonate. Twenty sets of measurements were made. Fig. 9 shows the results of the repeatability test for capacitance measured at 7.9 kHz. The mean capacitance measured was 16.404 pF. The standard deviation was found to be 0.0075243 pF, which is four orders of magnitude lesser than the mean.

## IX. 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 sample had 90% moisture content, 7.5% fiber and 2.5% calcium carbonate. Twenty sets of measurements were made. Fig. 10 shows the result of the reproducibility test for the measured capacitance at 4 kHz. The mean capacitance measured was 16.817 pF. The standard deviation was found to be 54.584 fF, which is three orders of magnitude lesser than the mean. The peak-to-peak variation in the estimated moisture content was found to be 0.1993%.

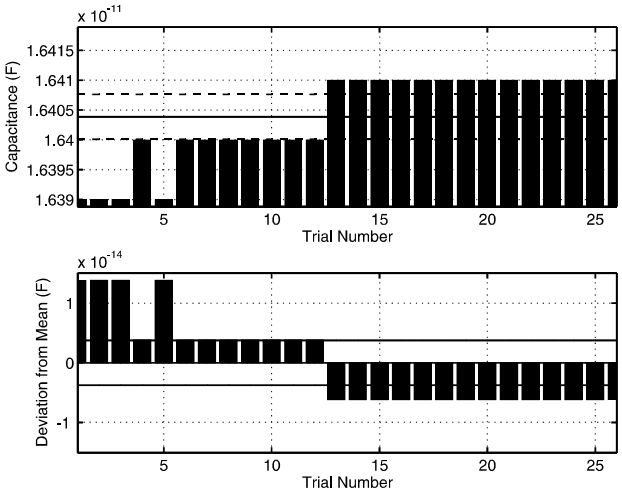


Fig. 9. Repeatability test for measurements made using pulp containing fiber, calcium carbonate, and water. The standard deviation is four orders of magnitude lesser than the mean.

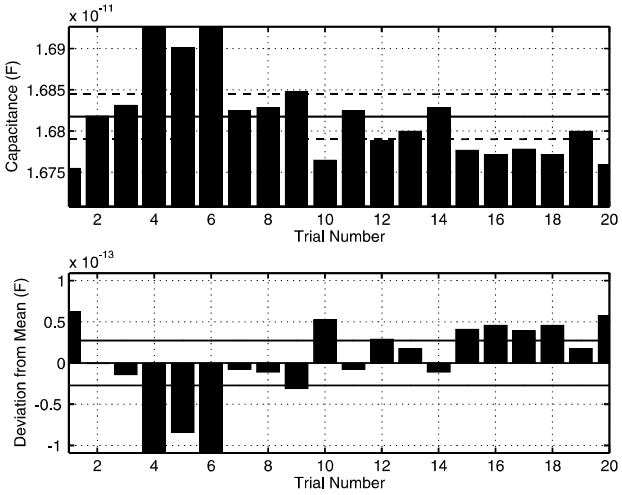


Fig. 10. Reproducibility test for measurements made using pulp containing fiber, calcium carbonate, and water. The standard deviation is three orders of magnitude lesser than the mean.

## X. CONCLUSION

The ability of the sensor to accurately measure the moisture content in pulp in the presence of calcium carbonate has been demonstrated. The sensor's repeatability and reproducibility have also been demonstrated. The estimation algorithm can be made more efficient by incorporating chemometric tools such as PLS and PCA. Apart from improving the algorithms, the effect of temperature variation, pulp variations, and pass line sensitivity will be studied as the next step.

## XI. ACKNOWLEDGMENT

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