NON-INVASIVE COTTON MOISTURE MEASUREMENT FOR GIN DUCTS

A. S. Krajewski
S. G. Gordon
CSIRO Materials Science and Engineering
Belmont, VIC Australia

Abstract

The management of moisture in cotton during ginning remains one of the most important factors in determining final fiber quality. Resistance plates are typically used to measure moisture in seed-cotton and lint as it is processed through the gin, but these are limited by inaccuracies that arise from the small proportion of cotton tested, contamination of the sensor, and by the non-linear response to low and high moisture levels. In this paper, presented will be a new sensing device that has potential for measuring the moisture of both seed-cotton and lint. The device combines large area capacitance plates with light detectors to measure the mass and moisture of material travelling quickly under pneumatic pressure or gravity through gin ducts.

Introduction

The moisture content in seed-cotton at harvest through to lint in the bale can have significant effects on the quality of the fiber sold to the spinning mill. There are optimum moisture levels for seed-cotton and lint (fiber) for each harvest and ginning process that enable efficient harvesting, ginning, cleaning, baling, and safe storage (Hughs et al., 1994). Likewise, there are similar considerations in the processing of other fibers and other bulk commodities such as grains and minerals.

To optimize processing efficiency and fiber quality, seed-cotton and lint need to be at particular moisture contents at different stages of the ginning process. For example, a low moisture content of around 5% during pre-cleaning enhances the cleaning of seed-cotton, while during ginning the moisture content of the fiber on the seed needs to be between 6% and 7% in order to prevent excessive fiber breakage. There have been many studies that have shown the detrimental effect of ginning and cleaning on fiber that is too dry or wet (Childers and Baker, 1977, Anthony et al., 2001, Anthony and Griffen, 2001), and the ameliorating effect on fiber damage after the proper amount of moisture has been metered onto or preserved in the lint or seed-cotton, (Moore and Griffin, 1964, Mangialardi et al., 1965, Mangialardi and Griffin, 1966, Leonard et al., 1970, and Anthony and Griffin, 2001).

There are many challenges associated with the management of moisture at each stage of ginning. The main challenges are the accuracy and speed with which lint and seed-cotton moisture can be measured and controlled. Despite development of systems that measure and then provide for drying or moisture replenishment of seed-cotton or lint through the gin (Griffin and Mangialardi, 1961, www.samjackson.com), there has not been widespread uptake due to the cost and the speed and accuracy of the response. Indeed it is the limitations in moisture measurement that prevents optimum moisture content being achieved for particular processes and the further automation of these systems.

Current moisture management systems in gins use either on-line or a combination of on-line and off-line moisture measuring methods based on instruments that measure electrical charge, e.g. the measurement of resistance or transmission (of micro or radio-waves), through the sample. On-line resistance-based sensors are typically used to measure the moisture of moving lint or seed-cotton. Their accuracy, whether used on- or off-line, is limited by specimen presentation, contamination of the sensor, and diminished sensitivity for very wet or very dry samples, not all of which can be adequately controlled inside the gin. Resistance-based moisture sensors do not work well when water droplets are sprayed directly on the surface of the cotton fiber. The combination of absorbed and surface moisture can cause errors in resistance-based moisture sensors because of the conductive effect of surface moisture that distort (increase) the measurement. Nor do these sensors work well when moisture content is low, e.g. <4.5%. According to Hearle (1953), the specific resistance of cotton at low moisture content becomes very large, with a converse reduction in current. A consequence is that resistance-based sensors need specially designed circuitry to manage the wide range of currents flowing between test electrodes, subject to the normal range of moisture contents, i.e. 4% to 10%. It is also the case that signal distortion and noise in measurements are amplified when the specimen is not applied correctly or consistently between or around electrodes.

Microwave and radio-wave transmission-based instruments require the sample be compacted to a reasonably high density, which limits their application to seed-cotton in module form (150 – 200 kg/m^3) or to lint pressed into a bale (320 – 540 kg/m^3). The application of microwave (Pelletier, 2004) and radio-wave transmission (Nelson, et al., 1998), sensors is currently restricted to the inputs and outputs of the ginning process, but not to the actual control of the gin.

In this paper will be introduced a new in-line moisture measurement device (Krajewski and Gordon, 2009) that can be used for measuring moisture content in seed-cotton or lint as it is being moved quickly by air (up to 20 m/sec) or gravity in transport ducts between gin machines. The device uses a large capacitance sensor, light emitters, and detectors as the active elements for sensing moisture and mass. Measured values are achieved through the changes to the permittivity (ε) between the plates associated with the cotton and the water (moisture) content of the cotton. Moisture content is defined as the ratio of mass of absorbed water in cotton lint or seed-cotton, determined by a standard thermal gravimetric method, to the total lint or seed-cotton mass. The light sensor is designed and calibrated so it measures the cotton mass through the measurement of the transmitted light through and scattered light from the cotton lint. The advantage of the device is that it can be situated within the gin at points prior to where the lint or seed-cotton undergoes conditioning and/or cleaning. That it is non-invasive and that the moisture value represents an average of all the material passing through the duct at a particular time, differentiates the sensor from current on-line moisture sensors. Moreover noted are the clear linear relationships between the device's sensor signals, the measured moisture and mass values of the sample.

In the device two sets of capacitor plates measure the permittivity (ε) of the duct material (fiberglass resin) and the air and material (cotton and moisture) moving between the plates (as per Equation 1):

$$\varepsilon_{total} = \varepsilon_{cotton+moisture} + \varepsilon_{airhumidity} + \varepsilon_{fibreglass} \tag{1}$$

Significant changes in permittivity between the capacitor plates are related to changes in the permittivity of the cotton and moisture complex. Variations in permittivity associated with air humidity, which occur as a result of changing conditions within the duct, contribute to a level of stray-capacitance. However, these are assumed to be correctable according to in-duct measurements of temperature and humidity. More significantly, variation in moisture and temperature inside the duct also affects the device's relatively large sensor plates, which must be structurally insulated, shielded and braced to reduce distortions in the electric field. This variation is partly compensated using stray-capacitance immune measurement circuitry such as that employed by Huangt et al. (1988) and feedback and auto-balancing techniques such as those described by Marioli et al. (1993), Toth et al. (1995), Karlsson (1999) and Pennisi (2005). These techniques are applied to capacitance sensors that require high accuracy. They allow static signals to be zeroed and slow fluctuations of both the transducer and stray-capacitance to be significantly reduced.

The total capacitance (C) measured by the device follows the formula described in Equation 2.

$$C_{total} = C_{stray} + \left(\frac{\varepsilon_{total} * A * (n-1)}{d}\right) * f \tag{2}$$

Where A is the (copper) plate surface constant in m^2, n = number of plates, d = distance between plates in m and f = capacitor edge field coefficient. The permittivity of the fiberglass (or glass) used as support for the capacitor plates is constant and is taken into consideration during design of the capacitive sensor. Due to the distance between the capacitor plates in the industrial device (around 150 mm) the edge field is also considered. The range of moisture values observed in cotton moving through the device is encapsulated in a capacitance range between 10 - 17 pF. The changes in the permittivity of the cotton-moisture mass complex occurring largely as a result of the relatively larger dielectric constant associated with water; 80.4 @ 20^{o}C, compared with air; 1.0 @ 20^{o}C, and cotton cellulose between 3.3 and 3.9 @ 20^{o}C.

The cotton mass and moisture relationship is highly correlated, so there is a need to normalize the mass signal to extract the moisture signal. In this device an array of LED light sources and detectors are used to provide an estimate of the fiber mass in the duct. Light passing through a particulate fluid medium can be described by the Lambert-Beer Law (Equation 3):

$$I = I_0 * e^{-k*x*c} \tag{3}$$

Where; I = the incident light from the source flux, I_0 = source light flux, x = distance through the medium (mm), k = excitation coefficient and c = concentration of material in the specified volume. This law is used to measure light traveling through liquids (turbidity measurements). It is applied here because the signal, averaged over several seconds, can be envisaged as a response to the particles (the cotton or seed-cotton) suspended in a fluid.

The distance between the light source and detectors in the device is fixed (at around 350 mm) so that a fixed volume for the light measurement is assumed, enabling the assumption that the amount of light transmitted through to the detector depends on the concentration or mass of fiber in the duct. Cotton fiber is highly reflective of light, so detectors were fitted to measure both occluded and scattered light. In preliminary tests, the measured relationship between the mass of cotton and the amount of light reaching detectors closely followed the above mentioned equation and it was not affected by the moisture content of in the cotton fiber.

The proposed device also has to be low cost in order to keep the overall instrument commercially viable. An example of low-cost capacitance measurement circuitry is discussed in Toth et al. (1995). The interface between sensors and the acquisition card should also be both simple and accurate. Some low cost interfaces are also considered in Ignjatovic et al. (2005). The extraction of cotton moisture from the overall cotton signal is achieved by combining the capacitance signal with signals from optical, temperature, and humidity sensors. The sensor device is designed to fit in the duct between the gin stand and lint cleaner, but can be built in ducting between any other gin machinery.

Methodology

Capacitor Sensor Development

A capacitive sensor test rig was built to conduct preliminary tests on the use of large capacitance plates and the data acquisition circuitry to sense static cotton fiber mass and moisture. The capacitor test rig took the form of the two 200 mm x 600 mm, insulated copper plates fixed to a fiberglass sheet and placed at a distance equal to the height of a standard commercial gin duct (~150 mm), such as that connecting the back of a commercial gin stand with the first lint cleaner. The capacitor was then placed into a metal sheet box imitating the electrical condition inside the duct. Figure 1 illustrates the form of the test rig and the basic instrumentation for data acquisition. Tests were conducted under constant ambient laboratory conditions of 25°C and 60% relative humidity.

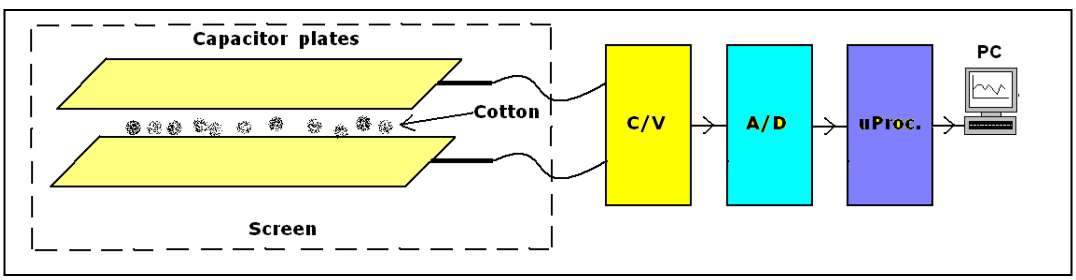

Figure 1 – Testing capacitor and data acquisition circuit; C/V = capacitance/voltage convertor; A/D = analog to digital convertor; uProc. = micro-processor

Following determination of the capacitor response, a capacitive mass-to-voltage converter was designed and tested. The data from the converter was acquired via an analogue-to-digital converter and then fed into a micro-processor and a PC (as per Figure 1).

Light Sensor

The previously mentioned capacitance-to-voltage and light-to-voltage converters were designed to link capacitance and light variations together. The light-to-voltage converter was designed so that the mass of cotton fibers passing through the duct is directly proportional to the light reaching the detectors. The light testing circuitry includes the LED-based light source (three white LED lamps 24 V & 1.3 A available through TENROD Australia – www.tenrod.com.au) and custom built photodetector arrays. The arrays used 24 standard SFH213 PIN photodiodes manufactured by OSRAM GmbH. In the test rig, the light sensor was enclosed to prevent ambient light influencing the measurement and variations in the LED's sensor with temperature changes were compensated for in the final calculation of the light response (in volts) to sample mass.

Industrial Sensor – Practical Implementation

Following initial assessment of the test rig and data acquisition circuitry an industrial-scale capacitance sensor was built for trial in a commercial gin. Design features of this device included the previously mentioned approaches for reducing stray-capacitance, incorporating humidity and temperature sensors and the alignment of high precision capacitance-to-voltage and light-to-voltage converters. The output of the capacitance-to-voltage converter in the industrial device covered a range between 1 V to 12 V that enabled high resolution capacitance changes between 10 pF and 17 pF to be recorded. The capacitance plates were manufactured from copper sheets. Holes in the plates allowed light to be transmitted through the cotton stream to the detector arrays opposite (see Figure 2).

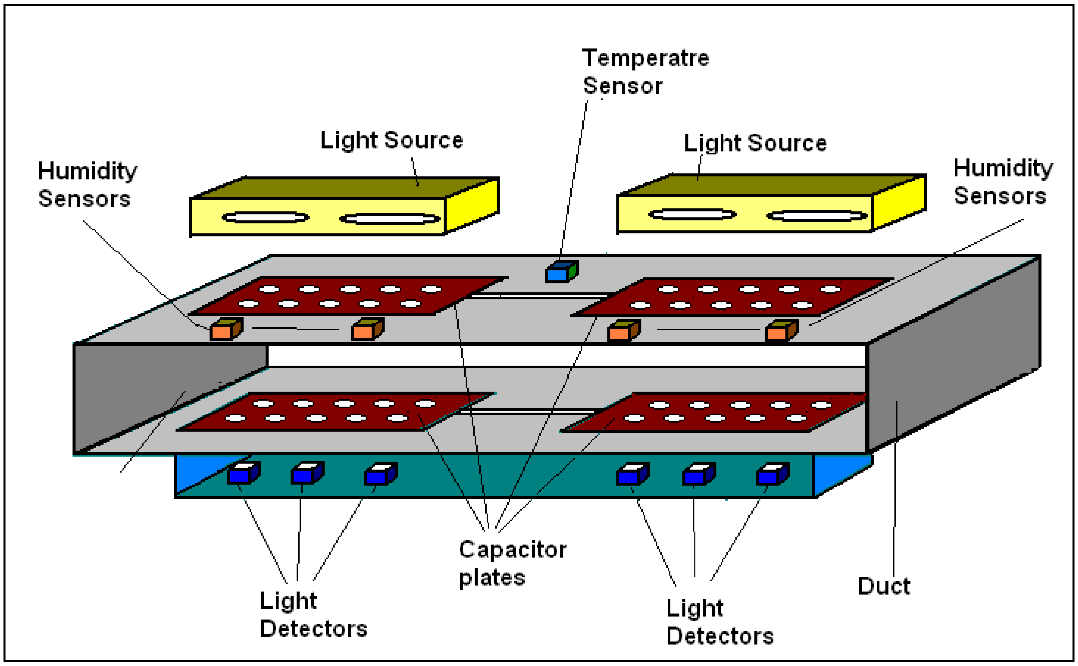

Figure 2 – Arrangement of sensors, light sources and capacitor plates within the device.

Capacitance-to-voltage and light-to-voltage converters together with an Innovative-Sensor-Technology TSic 301 temperature transducer and a Honywell HIH 4000 Integrated Circuitry Sensor humidity transducer were coupled with a National Instrument NI-USB-6216 data acquisition unit and connected to an ARK-3399 computer (www.advantech.com.au) that was used to process and save the data. The capacitance sensors delivered linear and rapid responses to variations in cotton mass and moisture to a sensitivity of ~±1 femtofarad of the nominal capacitance value. The accuracy of the system strongly depends on mechanical robustness of the duct sensor to vibrations, thermal expansion and contraction and electrical interference. The effect of external electrical field disruptions was reduced by shielding the electronic circuitry and cables. Vibrations were reduced by bracing the duct sensor to the self-standing scaffold. The sensor was isolated from vibration in the duct by flexible joints (Figure 3). Sensors and light sources were sealed from the outside environment so that dust would not affect the measurement. The position of the glass window used to separate the light sensors from the material and dust inside the duct means that it was largely self-cleaning.

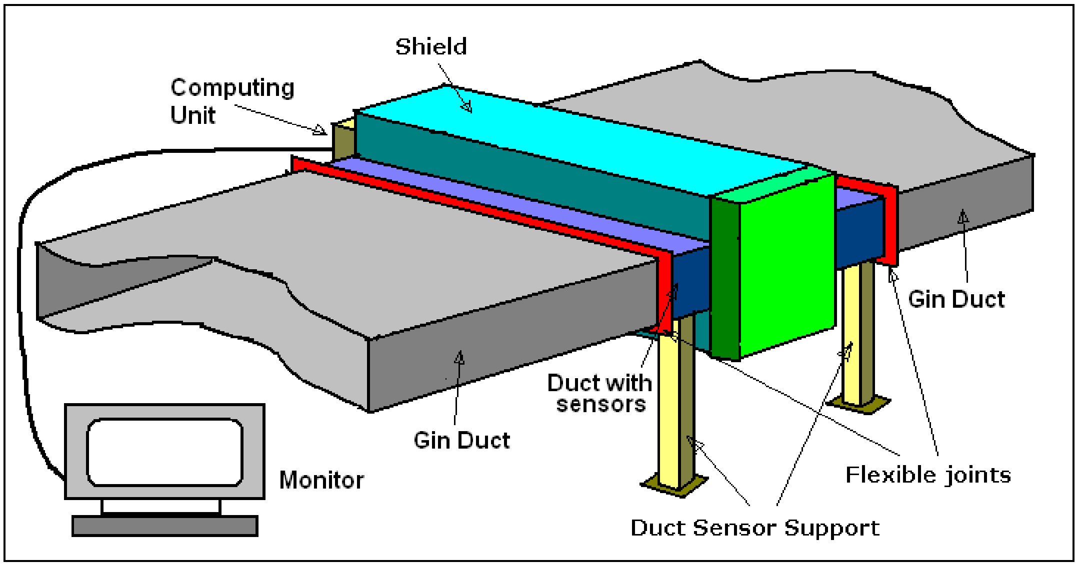

Figure 3 – Diagram showing shielding and support of sensor device within gin duct.

Thermal expansion (or contraction) of the duct sensor brought about by ambient and in-duct temperature variations are compensated by software calibration. In-duct humidity changes affect the cotton moisture measurement. The humidity and temperature sensors are used to compensate for those errors in the device. Humidity and temperature sensors are placed at the top part of the duct, with the humidity sensor protected against dust deposits by a wind shield. The in-duct temperature was obtained from a commercial temperature sensor. The plates and the lighting system are incorporated within the duct width and height of 2500 mm x 150 mm, however, the design and location of active components is flexible to accommodate different duct dimensions.

Experimental Data

Figure 4 shows the location of the device within the duct system of Gin 9 at Auscott Limited in Narrabri, NSW, Australia, where industrial trials of the device were carried out. On-line experimental data from the device's sensors were collected over two separate one-week periods during the 2009 ginning season. The data acquisition system was set to average each sensor's signal and store the data every 60 seconds. This allowed a reasonable sample frequency and sensitivity and also enough time to withdraw fiber samples for off-line moisture measurement in order to 'calibrate' the device's sensor data.

Figure 4 – Position of the device in ducting between the gin stand and first lint cleaner.

Ginning shifts during the 2009 season were limited to 12 hour day shifts starting at 0700 hrs. Ambient conditions were typically cooler and wetter in the early morning (12°C & 50% RH) and hotter and drier during midday and late afternoon (30°C & <25% RH). Fiber samples were periodically withdrawn throughout each shift from the sampling door in the duct just prior to the sensor device. The time at which each sample was withdrawn was synchronized with the on-line PC clock using a handheld timer-clock to allow alignment and correlation of the on- and off-line data, in order to generate a calibration.

Withdrawn fiber samples were quickly sealed in a zip-lock plastic bag to preserve their equilibrated moisture content, which was measured immediately using a VOMAX 465 Bench Top Moisture Gauge manufactured by VOMAX Instrumentation Inc., Adelaide, South Australia. The VOMAX 465 is calibrated to gravimetric moisture content according to an oven-drying standard, similar to ASTM Standard designated 2495-07. The advantage of the VOMAX 465 is the ability to gain a moisture values within a minute after the fiber sample has been weighed, which enables more frequent sampling and testing than would be possible using a gravimetric oven test method. Over two separate one week periods >200 specimens were collected and tested this way.

Data Analysis

To determine moisture values from the device's sensor values, capacitance and light sensor data were aligned and then rescaled with average moisture content values from the VOMAX 465 and corrected for humidity using Equation (4):

$$moisture = \left(A \frac{M_{cap}}{B * M_{light}} + d\right) * m_{VA} - C * H_{true}(T) \qquad (4),$$

where M_{cap} is the mass indicated by the capacitance sensor, M_{light} is the mass indicated by the light sensor, m_{VA} (in %) is a rescaling factor determined by the average moisture content (over the calibration test period) measured by the VOMAX 465 and H_{true} is the relative humidity. The value of m_{VA} used in these tests was 5.5%. Four other constants are used: A and d allow for the rescaling and alignment of the normalized capacitance signal to the final *moisture* value, while B depends on the difference between the cotton mass as indicated by the capacitor and light sensors. During the testing reported here, the value of B was determined as being ~1.12, but it is possible for the value of B to be affected by changes in the dimensions and orientation of the capacitor and/or light sensors. The constant C describes a portion of the in-duct humidity that is subtracted from the capacitance signal to compensate for external humidity and temperature changes that affect the permittivity of the sensor materials in the capacitor. This constant is positive and ranges in magnitude from 0.1 to 0.001. In the study reported here, C has a value of 0.0012. Values of A and d were 0.8 and 0.7 respectively. Constants A, B, and C are empirically established during the calibration process and they may change for different dimensions of the capacitive sensor, different type of light sensor, and humidity and temperature sensors. Statistical analyses of the measured and calculated data were conducted using Minitab 15.

Results and Discussion

Figure 5 shows raw capacitance and light sensors voltage values, measured by the device throughout one afternoon of the 2009 trials. The signal lines show the minimum voltage numbers for the capacitance (3) and light sensors (0.5) when no lint is passing through the device. Also noticeable is the deviation in capacitance from the light signal line as a run of drier modules was started (@1350 hrs) through the hotter and drier afternoon. The lines show that while the particulate 'concentration' of lint measured by the light signal remains constant, the mass of lint measured by the capacitance sensor is reduced as a result of the lower moisture content of the in-coming module and the dry conditions of the afternoon.

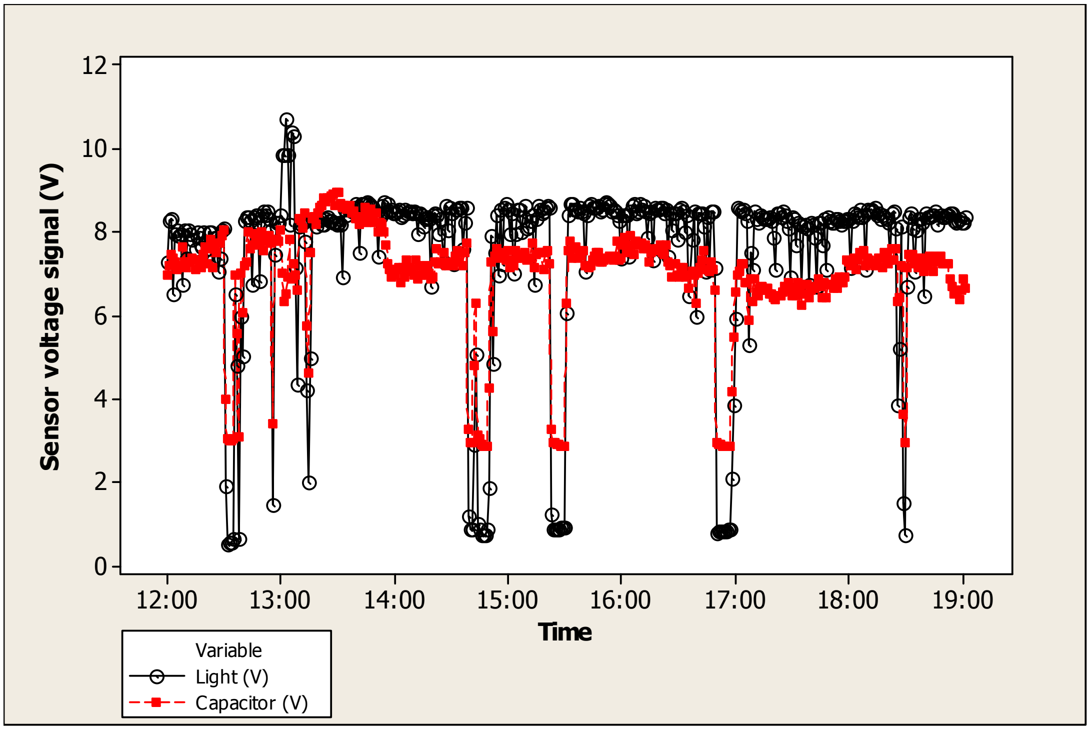

Figure 5 – Capacitance and light sensor values from the device within the duct of Gin 9, Auscott.

VOMAX 465 moisture values (N = 205) measured on separate lint samples withdrawn from the duct during the trial period were paired with capacitance and light sensor values and converted to moisture values using Equation (6). Calculated moisture values were then regressed against the measured VOMAX 465 moisture values in order to provide a measure of the device's accuracy. Paired values were retained in the regression on the basis of their standardized residual (SR); paired values with a SR > 2.0 (>2 standard deviations) were eliminated from the regression set. On this criterion N was reduced to 172 paired values. Statistics describing the distribution of these remaining calculated (device) and measured (VOMAX) values appear in Table I.

Rejected values are most likely to have occurred as a result of abnormal VOMAX readings, where sample extraction, handling and presentation in the measuring cylinder prior to measurement were not optimized or where withdrawn samples did not adequately represent the greater mass of fiber in the duct at the time. For example, offline measurements were made on cotton samples collected directly from the duct. These samples represented only a small amount of the cotton 'seen' by the device, which continued to average its data at around >25 kg/min. Indeed, herein are the main challenges associated with any 'live' calibration for this type and scale of industrial sensor.

Table I – Distribution statistics of the device and VOMAX moisture results

Sample Set	Mean	Std. Dev.	Min.	Q1	Median	Q3	Max.
Device (calculated)	5.517	0.276	4.952	5.297	5.494	5.721	6.116
VOMAX (measured)	5.436	0.265	4.800	5.200	5.400	5.600	6.100

Figure 6 shows a scatter plot of the paired data. The analysis of variance for their relationship appears in Table II. While the regression correlation coefficient (r^2 = 36.1%) is not large, the relationship is significant (P = 0.000), especially in light of the narrow range of moisture contents measured (between 5% and 6%) and the experimental errors associated with sampling and the VOMAX and device measurements, which likely accumulate to give measured values an error of at least ±0.5%. Indeed, the expected experimental error, plus some difficulty in exactly aligning the VOMAX moisture values of withdrawn fiber samples with the device's calculated average values, are nominated as the main reasons for some of the insensitivity of the VOMAX data to the calculated moisture content by the device. Expanding the range of moisture values would of course improve this regression further and reduce the affect of extreme-points (VOMAX values of 4.8% and 6.2%) in this set. Figure 7 shows the 205 consecutive VOMAX and paired calculated (device) moisture values including values rejected on the basis of their standardized residual. Evident in this plot is the very reasonable relationship between the VOMAX and calculated device values.

Table II – Analysis of variance between the device and VOMAX moisture results

Source	DF	SS	MS	F-value	P
Regression	1	4.3211	4.3211	95.99	0.000
Residual Error	170	7.6526	0.0450		
Total	171	11.9737			

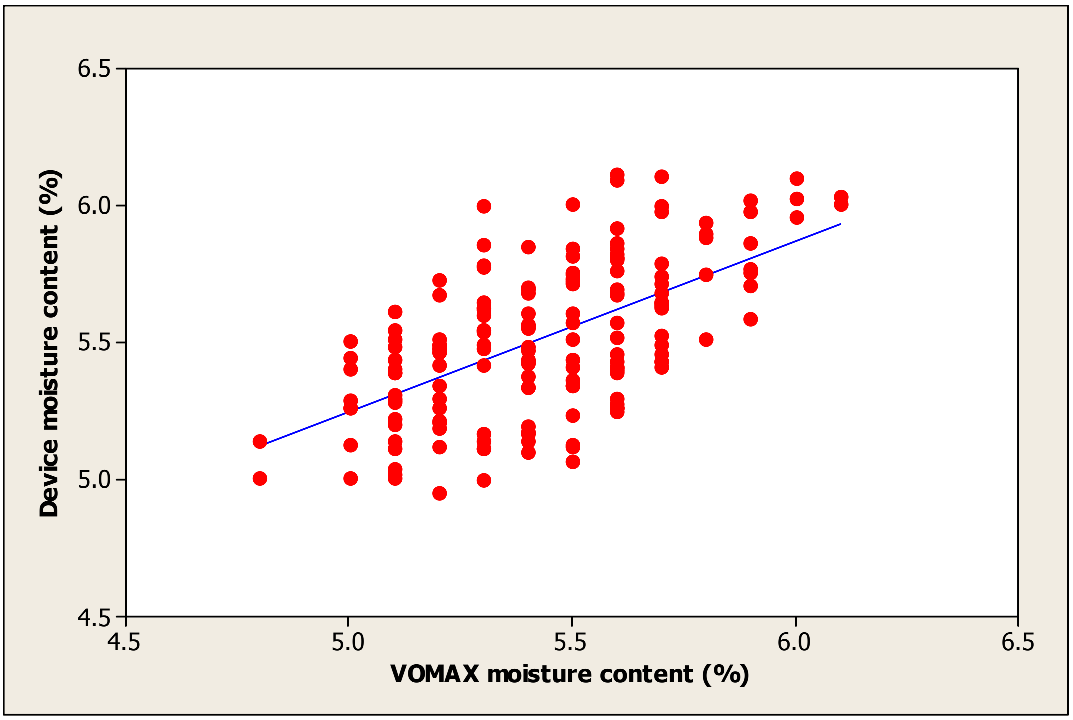

Figure 6 – Regression between paired VOMAX 465 and device moisture values

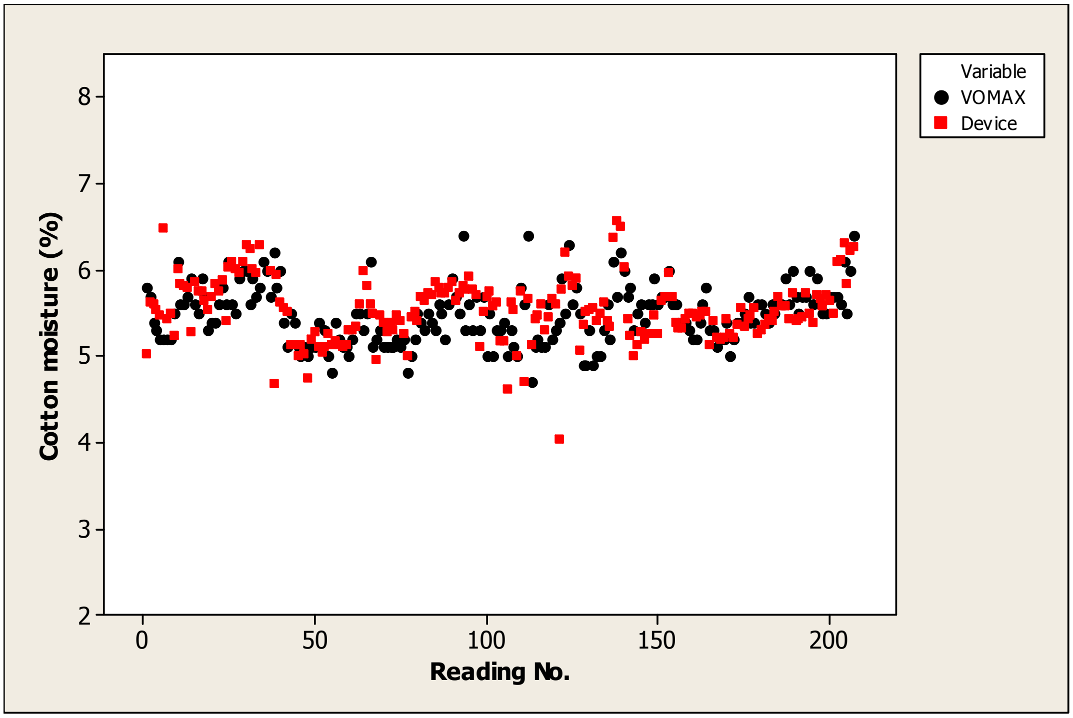

Figure 7 – Line graph showing consecutive paired VOMAX 465 and device moisture values

Conclusion

In this paper we present a new mass and moisture sensing device that has good potential for measuring the moisture of seed-cotton before ginning and/or the moisture in lint before it undergoes cleaning and/or baling in the gin. The design of the device combines large area capacitance plates with light detectors to measure the mass and moisture of lint travelling quickly under pneumatic pressure through gin ducting. Although not tested in this study, the application of the method to seed-cotton, ginned seed, and grains is also feasible.

In this study the device successfully tracked moisture in lint travelling at 20 m/sec through the ducts of a modern, commercial gin. Moisture values produced by the device were checked against values measured using a VOMAX 465 Bench Top Moisture Gauge. The advantages of the device under trial are that it measures the moisture content and mass of all the cotton or material in the duct and that it is non-invasive. Combined, these properties make the device potentially very useful in managing the use of moisture on cotton to enhance its resilience before ginning and lint cleaning and/or managing the application of heat for cleaning and drying cotton. Further trials in industry will continue with a focus on using the online sensor to control ginning and examining its performance across a wider range of moisture levels.

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