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ENGINEERING AND GINNING

Test of Pressure Transducer for Measuring Cotton-Mass Flow

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ABSTRACT

Site specific crop management involves closely monitoring the local environment and determining crop input needs for each portion of the field to economically optimize crop yields and reduce adverse environmental impacts of the production system. A key measure in this system is yield information determined by crop yield monitors. Current seedcotton yield monitors use optical and microwave sensing techniques to measure yield. However, the cotton yield monitors based on light emission require regular cleaning during the season and the microwave-based systems are expensive. The objective of this study was to test the use of velocity pressure to measure cotton-mass flow. The eventual goal is to provide an alternative approach for cotton yield monitoring. A cotton-harvester yield monitor concept was developed based on the relationship between air velocity pressure and the mass of seedcotton conveyed. The sensor was tested on a stationary cotton picker with seedcotton at two moisture contents, 5.9% and 8.5% wet basis. Regression analysis on the means of the data signals resulted in a coefficient of determination of 0.43 for the lower moisture content and 0.84 for the higher moisture content. Frequency and moving average filters were applied to the signals but did not improve the correlation. A method of compensating for gaps in the material stream resulted in an increased coefficient of determination of 0.52 and 0.87 for seedcotton at a moisture content of 5.9% and 8.5%, respectively. These results indicate the potential of air velocity pressure as an alternative approach for cotton yield monitoring.

Cotton yield can vary greatly from one part of the field to another part of the same field (Boydell and McBratney, 2002; Vellidis et al., 2003). When the local environment is closely monitored and only the necessary crop inputs applied in each portion of the field, yields can be optimized to maximize net returns and reduce adverse environmental impacts of the production system. This technique is called Site-Specific Crop Management (SSCM). Site-specific crop yield information is needed to determine the need for the use of site-specific nutrient application technology, and to evaluate the efficacy of the management practices in use.

Considerable effort has been placed on the development of sensors to measure grain flow rate through a combine to determine instantaneous yield data as the crop is harvested in the field (Fulton et al., 2009; Hummel et al., 1994; Pringle et al., 1993). Commercial companies and research institutions also have developed similar yield sensors for cotton (Guo et al., 2008; Sui et al., 2004; Wilkerson et al., 2001) and other non-grain crops. The willingness of producers to adopt this technology is mixed (Marra et al., 2010). The measurement of yield is the feedback for the SSCM technique and is an important part of the overall system.

The objective of this research was to test the use of air velocity pressure to measure cotton-mass flow. The eventual goal is to utilize pressure as an alternative to the optical and microwave sensing approaches for cotton yield monitoring. The sensing technique must be nonintrusive to the flow of seedcotton along the conveying duct and nonsensitive to moisture. A maximum sensor error of < 5% was desired. Moisture content, variety, and trash content were expected to affect cotton yield sensors.

MATERIALS AND METHODS

Preliminary laboratory tests were conducted to determine the correlation between velocity pressure and the mass flow rate of seedcotton. The apparatus consisted of a fan, conveying duct (PVC pipe), conveyor belt, collecting basket (wire mesh basket), and hopper (Fig. 1), and a venturi meter and a seedcotton inlet duct. Initial laboratory tests measured the pressure differential using a manometer. Later, tests were conducted using a Baratron pressure transducer

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(Model 221AH; MKS Instruments Inc., Andover, MA), which is capable of being mounted on the cotton picker. The pressure transducer was installed by connecting a pressure line from the transducer to the conveying duct via a 1.3-cm diameter pressure tap located 59.9 cm from the conveying duct outlet (Fig. 1). Seedcotton of mixed varieties (‘Stoneville 474’ [41.4% lint]; ‘Sure-Grow 125’ [40.8% lint]; and ‘Stoneville LA 887’ [40.6% lint]) that had been stored in an air-conditioned room was used for the laboratory experiments.

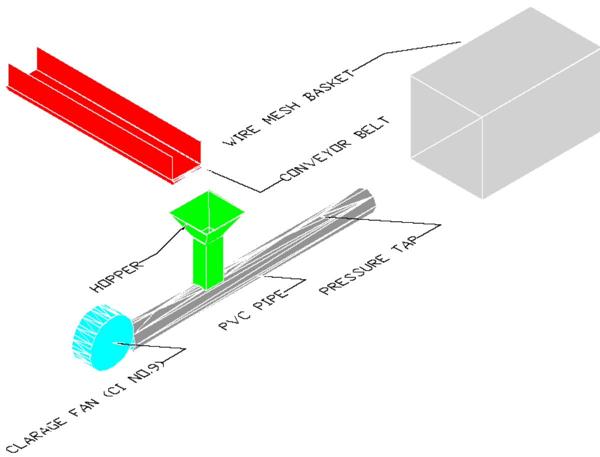

Figure 1. Schematic diagram of laboratory testing equipment.

The experimental procedure was as follows: a starting point was marked on both sheet-metal walls of the conveyor belt and another mark was made 153 cm from the starting point to allow measurement of conveyor belt speed. The two conveyor belt motors were set at a speed of 5 cm s^{-1} and connected to a power switch. The set conveying distance and the motor speed resulted in approximately uniform test runs of 31 s. Seedcotton was placed in a bag and weighed. The weighed cotton was spread as uniformly as possible on the conveyor belt over the marked length. A video camera was set facing the manometer. The fan was turned on then the motor power switch for the conveyor belt was turned on. Seedcotton was fed into the conveying duct through the hopper by the negative pressure created by the venturi meter. The video camera was used to record manometer readings in millimeters of water. According to Willford (1996, personal communication), a four-row cotton picker can harvest approximately 680 to 1360 kg hr^{-1} of seedcotton on average. This results in average seedcotton rates of approximately 2.8 to 5.7 kg min^{-1} for each row, which are in the same order of magnitude as those obtained by Sui et al. (2010). In this study, flow rates of 1 kg min^{-1}, 3.8 kg min^{-1}, and 6.7 kg min^{-1} per row were used; each flow rate was replicated three times. The mean pressure values for the categories were used to perform regression analysis. This procedure was repeated using the Baratron pressure transducer and the data were collected using a Handar data logger (Model 555; Handar Inc., Sunnyvale, CA). A regression analysis also was performed on these data.

Cotton-Picker Tests. The apparatus consisted of a two-row John Deere cotton picker (Model 9930; John Deere, Des Moines, IA), a conveyor belt, an Omega differential pressure transducer, Model PX653-05D5V (Omega Technology Company, Stamford, CT), a National Instruments card (Model DAQ Card-1200, Austin, TX), an IBM computer, a Psychron psychrometer (Model No. 566, Belfort Instruments, Baltimore, MD), a weighing scale (1 g accuracy), tape measure, and a stop watch. An Omega differential pressure transducer was used for the cotton-picker tests because of failure of the Baratron pressure transducer. Its calibration was verified using the same method used to calibrate the Baratron pressure transducer. The transducer output port was connected by a plastic tube to the 6-mm diameter picker blockage monitor tap. The picker blockage monitor was a pressure tap on the cotton-picker conveying duct that indicated when plugging occurred.

The experiment was conducted at the Northeast Research Station in St. Joseph, LA. Samples of seedcotton at moisture contents of 5.9% and 8.5% were used to determine the effect of moisture content on the sensor. The stationary cotton picker was operated with a fan speed of 4100 rpm. Stoneville 474, Sure-Grow 125, and Stoneville LA 887 seedcotton was fed into the picker conveying system using a conveyor belt moving at 4.9 cm s^{-1}. For each mass flow rate of seedcotton, velocity pressure in the conveying chute was measured using an Omega differential pressure transducer. The data were collected by a National Instruments card and regression analysis conducted.

The seedcotton was divided in half and treated under different ambient conditions to get a range of harvesting moisture contents. A Parameter Generation and Control machine (PGC 1000 CFM Climate Lab-AA Model No. AA-5580A; Parameter Generation &. Control Inc., Black Mountain, NC) was used to obtain average moisture contents of 12% and 8% wet basis (w.b.). Following these treatments, 0.73 to 3.65 kg (in 0.73 kg increments) of seedcotton from each batch corresponding to a specified mass flow rate was weighed and stored in a tightly sealed bag to prevent changes in moisture content of the seedcotton from exposure to high summer temperature conditions in the greenhouse storage room. Due to an electrical problem with the Baratron pressure transducer, there was a 2.5 wk delay in conducting the tests. This resulted in the moisture range changes to 5.9% and 8.5% w.b. Mass flow rates of 1.4 kg min^{-1}, 2.8 kg min^{-1}, 4.2 kg min^{-1}, 5.6 kg min^{-1}, and 7.0 kg min^{-1} were used. Each of these flow rates was replicated three times. Each bag was tagged with a code number to distinguish it from the others during the actual experiment. Finally, random numbers were generated to randomize the order in which the treatments were run.

The experimental procedure was as follows: two 10-g samples of seedcotton were taken (one from each treatment) and stored in metal cans for later moisture content determination using the standard oven drying method (Method D 2495, ASTM, 2007). Temperature and relative humidity readings were recorded. The relative humidity at the beginning, middle, and end of the experiment were 45%, 38%, and 23.5%, respectively. Although the relative humidity changed during the experiment, this change was assumed to have minimal effect on seedcotton moisture content because it was bagged and tightly sealed and runs were completed within 1 min after the cotton was spread. Seedcotton was emptied onto the conveyor belt and spread as uniformly as possible between the two marks spaced 153 cm apart (Fig. 2). The cotton-picker engine was started and its fan was turned on. The engine was then turned to maximum speed. Next, the DAQ (Data Acquisition) unit was started and the conveyor belt was turned on to feed the seedcotton into the conveying duct. Data were collected until the end of the run. This procedure was repeated for the bagged and labeled seedcotton following the randomly generated order.

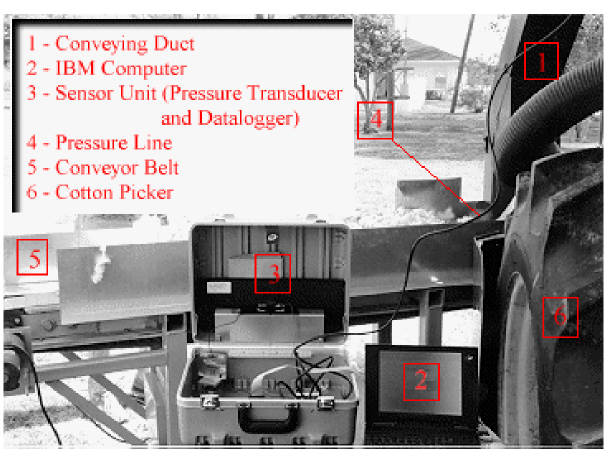

Figure 2. Cotton-picker testing equipment.

Data were processed and statistical analyses were conducted. The flow rate was adjusted for the actual time of each run. The means of the data signals were calculated and used in a t-test to determine if the sensor readings for the dry and wet cotton samples were significantly different. A two-factor analysis of variance (ANOVA) with replication was then conducted to determine if the moisture content had a significant effect on the sensor. Correlation and regression analyses were done to determine the relationship between mass flow rates and pressure and the seedcotton mass flow rate prediction equation as a function of velocity pressure.

Several filters were applied to the selected signals with the objective of improving the accuracy of the sensor. Filters eliminate (acoustic) noise thereby increasing the signal-to-noise ratio. The filters applied were a high-pass elliptic filter, a low-pass elliptic filter, and a low-pass Yule-Walker filter (Etter, 1997). The characteristics of these filters were: a magnitude of 1, a cutoff frequency of 5 Hz (0.2 normalized), a sampling frequency of 50 Hz, and an order of 10. Normalized frequency is the ratio of the frequency to the Nyquist frequency (25 Hz). The cutoff frequency was determined using the MATLAB Spectrum command, which calculates the Power Spectral Density (PSD) of the signal using the fast Fourier transform algorithm. MATLAB Spectrum was applied to all the representative signals and an average cutoff frequency of 5 Hz corresponding to a power spectral density of 0.05 was chosen. The details of these filters are given by Etter (1997).

In addition, it was noted that if clumping occurred during a given experimental run it was followed by periods without the flow of seedcotton into the conveying duct ("no-cotton"). The no-cotton pressure sensor readings were determined by first taking six pressure sensor readings, three each for the dry and wet seedcotton samples, when there was no flow of seedcotton into the conveying duct. Then the mean no-cotton pressure sensor reading (41.9 mm H_2O with a standard deviation of 1.1 mm H_2O) was determined. In this study, the no-cotton pressure sensor values are defined as all pressure sensor readings greater than the no-cotton mean sensor reading minus-three standard deviations or pressure readings greater than 38.6 mm H_2O. Because the no-cotton (> 38.6 mm H_2O) sensor readings would skew the mean sensor readings that were used for statistical analysis, they were eliminated and replaced with 38.6 mm H_2O.

RESULTS AND DISCUSSION

For the laboratory tests using the manometer, correlation and regression analyses were performed using the average of the three pressure readings recorded for each mass-flow rate. The analyses resulted in the following regression equation with a correlation a correlation coefficient of 0.99:

$$Y = 1.75X - 178.24 \ (R^2 = 0.98) \quad (1)$$

where Y is seedcotton mass flow rate in kg min^{-1} and X is the manometer reading in millimeters of H_2O. The laboratory tests were repeated using the Baratron pressure transducer. Statistical analyses were carried out using all the recorded pressure readings for the three replicate runs for each mass-flow rate. These analyses resulted in the following regression equation with a correlation coefficient of 0.86; X and Y are as defined above:

$$Y = 4.40X - 409.09 \ (R^2 = 0.74) \quad (2)$$

Cotton-Picker Tests Results. A student's t-test carried out separately for each of the five levels of mass flow rates showed that the mean sensor readings for dry and wet seed cotton were significantly ($p < 0.05$) different at 1.4 kg min^{-1}and 7.0 kg min^{-1} but they were not significantly different for 2.8 kg min^{-1}, 4.2 kg min^{-1} and 5.6 kg min^{-1} mass flow rates as shown by the p-values in Table 1.

Table 1. Two-sample t-test for the mass flow rates (df = 4).

Mass Flow Rate (kg/min)	t-value	*P*-value (Prob|*P* > *Pcr*|, two tailed)
1.4	2.82	0.048
2.8	1.71	0.186
4.2	0.83	0.453
5.6	0.06	0.955
7.0	3.08	0.037

A two-factor ANOVA with replication indicated that mass flow rate was a good predictor of sensor reading but moisture content was not. A combination of mass flow rate and moisture content was also a good model for predicting the sensor reading as shown in Table 2.

Table 2. Two-factor ANOVA with replication.

Source of Variation	df	F-value	*P*-value	F crit
Mass Flow Rate (FR)	4	4.47	0.01	2.87
Moisture Content (MC)	1	0.21	0.66	4.35
FR x MC (Interaction)	4	4.83	0.01	2.87
Error	20			
Total	29			

The picking and conveying units (the spindles, doffer, metal shields, and conveying duct) of the cotton picker are hydraulically controlled. The hydraulic system of the two-row cotton picker used leaked. The leakage caused a reduction in the negative pressure that was used to feed seedcotton into the conveying duct. This occasionally resulted in the plugging of seedcotton and a little seedcotton dropping to the ground. Due to this leakage the conveyor belt did not feed cotton during the run for 1.4 kg min^{-1} and 7.7 kg min^{-1} dry cotton signals and hence they were discarded. In addition, the signal during the 7.2 kg min^{-1} wet seedcotton run was discarded due to slippage between seedcotton and the conveyor belt. Slippage resulted in too long a run compared with other wet seedcotton rate runs.

Regression analysis using a MATLAB program on unfiltered data signals showed a better correlation for wet seedcotton than for dry cotton. The correlation coefficient for the wet seedcotton was -0.92 and the following regression equation:

$$Y = 49.19 - 1.19X \ (R^2 = 0.84) \quad (3)$$

where Y is the mass flow rate in kg min^{-1} and X is the sensor reading in millimeters of H_2O. Analysis for dry seedcotton resulted in a correlation coefficient of -0.65 and following regression equation where X and Y are as defined above:

$$Y = 76.78 - 1.96X \ (R^2 = 0.43) \quad (4)$$

Replacing the no-cotton (> 38.6 mm H_2O) sensor readings with no-cotton mean sensor reading minus-three standard deviations (38.6 mm H_2O) resulted in an improved coefficient of determination of 0.52 for dry cotton and 0.87 for wet seedcotton was. Figure 3 shows the effect of eliminating the no-cotton sensor readings and replacing them with 38.6 mm H_2O on the 7.7 kg min^{-1} dry cotton signal. The bottom section of Fig. 3 shows background noise while no cotton is being transported. Application of this technique resulted in a correlation coefficient of -0.72 and the following regression equation for the dry seedcotton:

$$Y = 45.85 - 1.14X \ (R^2 = 0.52) \quad (5)$$

where Y is the mass flow rate in kg min^{-1} and X is the sensor reading in millimeters of H_2O. For the wet seedcotton, the technique yielded a correlation coefficient of -0.93 and the following regression equation:

$$Y = 59.54 - 1.51X \quad (R^2 = 0.87) \quad (6)$$

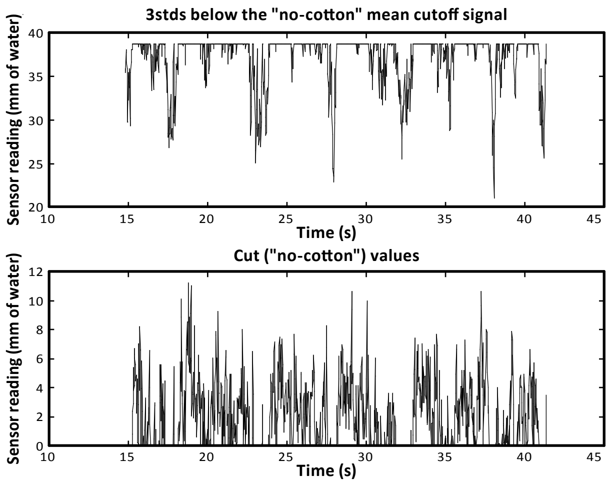

Figure 3. Sensor signal profile for compensated no-cotton gaps (top) and eliminated background noise signal while no cotton is being transported for the 7.7 kg min^{-1} dry cotton (bottom).

The correlation between seedcotton mass flow rates and velocity pressure were negative for the cotton-picker tests as depicted by the negative correlation coefficients and the regression lines in Figs. 4 and 5 for the dry and wet seedcotton, respectively. The negative correlation for the cotton-picker tests is due to the fact that velocity pressure measurements were taken on the suction side of the pneumatic conveying system. The correlation coefficients for the laboratory tests were positive because velocity pressure measurements were taken on the discharge side of the conveying system.

A two-factor ANOVA carried out on the mean values of the filtered sensor readings revealed that seedcotton mass flow rate was a significant predictor of the sensor reading. The combination of moisture content and mass flow rate was not a good model for predicting the sensor reading.

The lower correlation between velocity pressure and seedcotton mass flow rate for dry seedcotton compared with wet seedcotton shows that the velocity pressure sensor is sensitive to the seedcotton moisture content. The moisture content for dry seedcotton of 5.9% was below the lower limit of the 6.5 to 8.0% range for optimum ginning (William et al., 1994). Judging from source, the moisture content of the dry seedcotton used is below this lower limit. Cotton with too low a moisture content may stick to metal surfaces as a result of static electricity generated on the fibers (Hughs et al., 2004). Although this was not noticed during the test runs, it is a possible reason for the statistical differences observed in the correlation between 5.9% moisture content seedcotton and 8.5% moisture content seedcotton. Therefore, it is important that farmers heed moisture content recommendations for harvesting seedcotton of less than 12.0% w.b. (Cocke et al., 1977; Hughs et al., 2004; William et al., 1994) but not below 6.5%.

Based on the results of this study, a linear relationship best explained the changes in velocity pressure with respect to changes in conveyed seedcotton mass flow rate. This is different from the Bernoulli's equation in which air flow velocity is a function of the square root of pressure. However, it important to remember that although conveying air flow velocity and hence air mass flow rate is a function of the square root of pressure, the relationship between mass flow rate of the conveyed seedcotton and pressure cannot be inferred easily from Bernoulli's equation. Therefore, additional research is needed in which the full range of material harvested is used, in addition to utilizing established relationships between mass flow of conveyed material and air flow rate suggested by Mills (2004). This will help establish relationships between air velocity pressure and harvested seedcotton mass flow rate that would be expected.

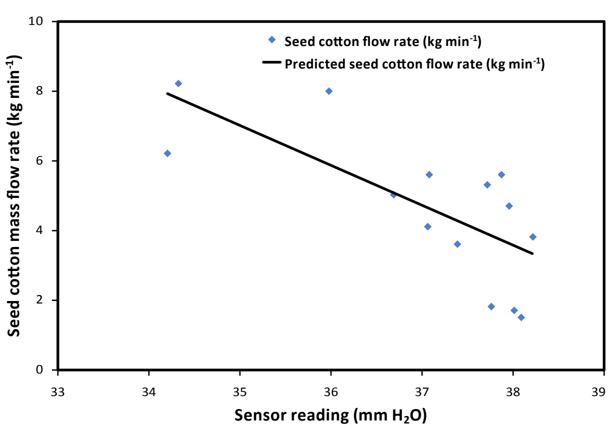

Figure 4. Relationship between air velocity pressure and seed cotton mass flow rate for dry cotton.

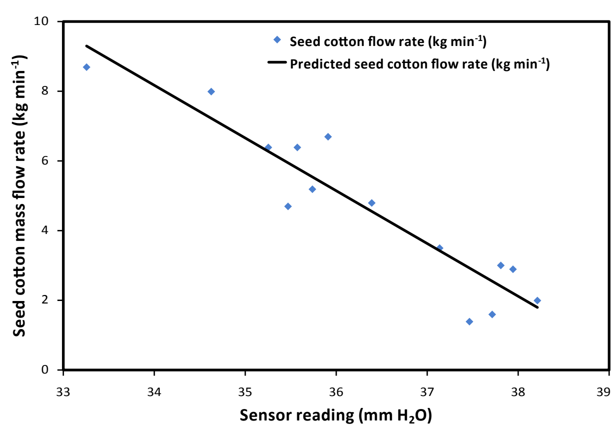

Figure 5. Relationship between air velocity pressure and seed cotton mass flow rate for wet cotton.

CONCLUSIONS

Optical and microwave sensing methods are used in current seedcotton yield monitors. However, cotton yield monitors based on light emission require regular cleaning during the season and microwave-based systems are expensive. In this study, the use of velocity pressure to measure cotton-mass flow was tested as an alternative approach for cotton yield monitoring. Results indicate a modest correlation between velocity pressure and the seedcotton mass flow rate with correlation coefficients of -0.65 and -0.92 for dry and wet seedcotton, respectively. The correlations were improved by compensating for gaps in the material stream as indicated by correlation coefficients of -0.72 and -0.93 for dry and wet seedcotton, respectively. The sensor was nonintrusive to the flow of seedcotton along the conveying duct. Based on regression analysis, a sensor error of < 13% was achieved for seedcotton sample at a moisture content of 8.5% and < 48% for seedcotton at a moisture content of 5.9%, compared to the desired sensor error of < 5.0%. This implies that this sensing technique is sensitive to the seedcotton moisture content and would require that farmers follow the recommended harvesting moisture of 6.5 to 10% to avoid static electricity that might significantly reduce sensor accuracy. Finally, these results indicate the potential of velocity pressure as an alternative approach for cotton yield monitoring. However, additional research needs to be done to enhance the performance of the velocity pressure seedcotton mass flow rate technique in terms of accuracy, reliability, robustness, and sensitivity before it can be recommended for industrial applications.

ACKNOWLEDGMENT

The co-author of this study is completing this research began by Dr. Mike Mailander to honor his great contributions to the body of science through his research. Dr. Mailander was a great mentor to many students including this co-author and a great teacher to numerous other students. He will be greatly missed.

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