NON-INTRUSIVE FLOW RATE SENSOR FOR HARVESTER AND GIN APPLICATIONS

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Abstract

An optically-based system for measuring cotton flow rate has been designed and tested in both harvester and gin applications. Accuracy was documented by comparing actual and predicted load weights. The system predicted harvester load weights with an average absolute error of 4.7 percent. Accuracy in the gin was similar with an average absolute error of 3.4 percent. The technology has been patented and licensed to industry by the University of Tennessee for mobile equipment applications.

Introduction

Air is often used to convey low-density particulate matter through ducts. In many applications, it is desirable to measure the flow rate of the conveyed material as it travels through these ducts. An optical sensor has been developed to estimate material flow rates in real-time. While the sensor could be applied to any particulate matter conveyed by an airstream, the focus of this research has been on measuring cotton flow rate. The technology has been installed on a cotton picker and evaluated to determine suitability as a site-specific yield measurement tool. A similar system was installed on a seed cotton feeder duct in a gin to investigate the possibility of use as an input for gin process control.

Background

The cotton industry is hungry for a reliable system capable of accurately measuring air-entrained cotton flow rate. In 1997, Searcy et al. stated that “Cotton producers interested in precision management need to have yield mapping capabilities.” Generating site-specific yield information during harvest means measuring the flow rate of cotton as it is accumulated by the harvester. Modern cotton pickers use duct-confined air streams to convey cotton from the picking units to the storage basket. Measuring the flow rate of the cotton as it travels through these conveyer pipes will provide the cotton flow rate information needed for real-time yield determination.

After cotton is harvested, it is generally taken to a local gin for processing. Duct-confined air streams carry cotton to various stations in the gin. The ability to measure cotton flow rate as it is conveyed through the gin is important as automation becomes more sophisticated. Flow rate is a parameter necessary for controlling driers and other gin machinery.

A review of the literature reveals several optically-based systems designed to measure cotton flow rate. The earliest report of such work was by Wilkerson et al. (1994). The optical system described by Wilkerson et al. performed well in preliminary laboratory tests. However, when applied to a harvester, system performance was subject to overwhelming problems with dynamically changing ambient light.

Another optical device, a light source paired with a sensing bar, has been tested in various applications since 1989 (Thomasson et al., 1997; 1999). The device was mounted on a harvester and evaluated for suitability as a yield measurement tool. It was also tested on a seed cotton unloading duct and a lint cleaner waste duct in the gin. Results from all three applications were positive, and additional research was conducted to optimize the device for measuring the flow rate of lint cleaner waste (Thomson et al., 1999; Whitelock and Thomson, 1998).

In a related study, Thomasson et al. (1997; 1999) conducted experiments with a second optical system. Relationships between device output and seed cotton flow rate were developed. A version of this system was mounted on a harvester and tested in 1998 (Sassenrath-Cole et al., 1999). Harvester test results held promise, but problems with dust build-up and cotton stringers were reported.

Two optically based systems are commercially available for harvester yield monitoring applications. They have been tested by several authors. Results ranged from excellent (Gvili, 1998; Wallace, 1999; Wallace et al., 1998) to less than ideal (Durrence et al., 1999; Durrence et al., 1998; Sassenrath-Cole et al., 1999; Searcy, 1998; Searcy and Roades, 1998). The most frequently reported problems involved dust and debris build-up on sensor faces. The problems were so severe in South Carolina, Clemson engineers designed a pressurized air box to enclose the sensors and force air across their faces to keep them clean (Wolak et al., 1999).

The system originally described by Wilkerson et al. has undergone significant modification since the 1994 report. A description of the resulting design along with results of two accuracy tests are given below.

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System Operation

The material flow of interest may be confined by a single duct (as in most cotton gin applications) or by several parallel ducts (as with most cotton pickers). Regardless, each duct is equipped with an emitter array and a detector array mounted opposite each other as shown in Figure 1. The emitter array projects a number of discrete light beams across the duct. Each emitter is paired with a photo-detector that has a limited field-of-view and only receives light energy from the corresponding emitter. Detectors are integrated circuits that have frequency-based digital outputs. Device output frequency is linearly related to the intensity of light striking the active area over several orders of magnitude. Outputs from each individual detector are coupled to digital hardware counters which are interfaced with a computer. Counters sum pulses produced by the detectors over some integration interval. At the end of each integration interval, the data acquisition computer reads and clears all counters. Resulting sums, p_{ij}, represent the total amount of light energy received by each detector during the interval. Each measurement of total light energy is related to the amount of cotton that passed between the emitter and detector during the integration interval.

The following discussion assumes that the sensing system includes j sensing units mounted on j ducts (one sensing unit per duct), and that each sensing unit contains i emitter-detector pairs. The first data processing steps establish the difference between a baseline, b_{ij}, counter output and the counter output of interest for each emitter-detector pair. The baseline represents counter output when there is no cotton flow. Because of many factors such as inconsistent sensor mounting, variations in light source output, and uneven dirt accumulation on sensor faces, baseline levels change with time and are unique to each emitter-detector pair. Baseline adjustment compensates for change over time, and data normalization accounts for relative differences between emitter-detector pairs. The baseline adjustment procedure consists of collecting a number of p_{ij} values and setting b_{ij} equal to the greatest p_{ij} in the lot. The data normalization procedure involves dividing each p_{ij} value by b_{ij}. To limit the accumulation of error due to low-level noise, any p_{ij} values that are greater than a threshold level determined by subtracting a baseline offset, Δ, from the baseline are assumed to represent no cotton flow. The value of the baseline offset, Δ, is based on either experimental data or operator experience, and should minimize low-level noise accumulation without affecting true cotton flow rate measurements. Values of p_{ij} that are less than the threshold are normalized, and this normalized value is subtracted from the normalized baseline which is equal to one. This yields a normalized difference, x_{ij}. Figure 2 is a graphical representation of data from one emitter-detector pair being stepped through the processing scheme described above.

These steps may also be represented by the following expressions.

If $p_{ij} < b_{ij} - \Delta$, then the normalized difference, x_{ij}, is calculated using the following equation.

$$x_{ij} = \frac{b_{ij}}{b_{ij}} - \frac{p_{ij}}{b_{ij}} = 1 - \frac{p_{ij}}{b_{ij}}$$

where:

p_{ij} = total number of pulses accumulated from the i^{th} detector in the j^{th} sensing unit during the integration interval

b_{ij} = baseline value for the i^{th} emitter-detector pair in the j^{th} sensing unit

Δ = baseline offset

x_{ij} = normalized difference for the i^{th} emitter-detector pair in the j^{th} sensing unit

Otherwise, if $p_{ij} > b_{ij} - \Delta$, then x_{ij} is set to zero.

The next data processing steps involve three classes of terms that are determined through a calibration process described below. The first of these terms is a power, u, to which each x_{ij} is raised. The power function is used to account for the fact that the slope of the flow rate versus x_{ij} function increases with increasing flow rate.

After the exponent has been applied, results are multiplied by weighting coefficients, C_i. The weighting coefficients compensate for some of the variation in the depth (x-direction in Figure 1) and velocity of cotton flow within each duct. Even in applications where $j>1$, weighting coefficients only have i unique values. Relative flow rates within each duct are determined by summing x_{ij} values over some period of time for each emitter-detector pair in the sensing unit. These sums are compared across the sensing unit, and ranked from greatest to least. This process is repeated for each sensing unit in the system. Emitter-detector pairs from different sensing units which have equal ranks also have equal weighting coefficients.

Application of the exponent, u, and the weighting coefficients, C_i, is summarized by the following expression.

$$A_j = \sum_{i=1}^{m} C_i x_{ij}^{u}$$

where:

A_j = sensing unit output from the j^{th} sensing unit mounted on the j^{th} duct

m = number of emitter-detector pairs in the j^{th} sensing unit

C_i = weighting coefficient for the i^{th} emitter-detector pair (determined by calibration)
x_{ij} = normalized difference for the i^{th} emitter-detector pair in the j^{th} sensing unit
u = exponent (determined by calibration)

Finally, sensing unit outputs, A_j, from all ducts are summed and multiplied by a scaler to obtain an estimate of the amount of cotton that passed through the ducts during the integration interval. This final step is represented by the following equation.

$$M = K\sum_{j=1}^{n} A_j$$

where:

M = the amount of cotton that passed through the ducts during the integration interval
K = scaler (determined by calibration)
n = number of sensing units (one per duct) in the sensing system
A_j = sensing unit output from the j^{th} sensing unit

Variations of this system have been extensively tested over a three-year period. Two versions of the system, one for a harvester and one for a gin, along with test procedures and results are described below.

Harvester Testing

A system was installed on a Case-IH 2155 cotton picker prior to the 1997 harvest season. Case-IH 2155 pickers have two cotton conveyer pipes per row. One of these pipes serves the front picking drum, and the other serves the rear. Results indicate that rear pipe sensing unit outputs are linearly related to front pipe sensing unit outputs over the range of harvest conditions and cotton flow rates experienced during field testing in 1997. Figure 3 is a graph of this relationship for 28 test loads. Approximately 97 percent of variation in rear pipe sensing unit output is predicted by variation in front pipe sensing unit output. Although a part of the 1997 data set includes data from pipes serving front and rear picking units, most of it does not. Data from front pipes was collected for the entire season. This data is used in the analysis that follows. It should be stressed, however, that the linear relationship between front and rear drum flow rates may not be present in all situations. Future application of this technology should include all conveyor pipes on a harvester.

System parameters for the 1997 harvester test were set as follows. Each sensing unit had a maximum of five emitter-detector pairs. The integration interval was 25 ms. The number of p_{ij} samples compared to obtain a b_{ij} estimate was 40, hence b_{ij} was reset every second. The baseline offset, Δ, was set at 50. Because of the relatively low cotton flow rates and high conveying air velocities, the exponent, u, was set at 1.0. The weighting coefficients, C_i, were systematically assigned according to the relative flow rate rank of each emitter-detector pair, such that pairs with the greatest rank had $C_i = 1.0$, pairs with the second greatest rank had $C_i = 0.8$, continuing to pairs with the least rank which had $C_i = 0.2$.

Eighty-seven small loads of cotton were harvested during the field test. Varieties included PM 1215 RR, ST 132, and DP 20. Total load weights were measured and recorded. Load weights varied from 275 to 1361 lb with average cotton flow rates up to 0.57 lb/s/pipe. Sensing unit outputs sums were integrated over time for each of the first eight loads. These integrated sensor outputs along with corresponding measured load weights were used as calibration data. Least-squares linear regression was used with this data to find the optimum value of the scaler, K. The resulting K was applied to the system for flow rate calculation in the remaining 79 loads. Flow rates were integrated over run times to give predicted load weights. These predicted load weights were compared with true load weights to quantify system performance.

The error distribution for the 1997 harvester test is shown in Figure 4. The system predicted load weights to within ±10 percent for all but four of the 79 loads. The average absolute error was 4.7%. Correlation analysis was used to determine whether average flow rate had an effect on system accuracy. No statistically significant correlation between average flow rate and absolute error was present ($r=-0.11$, $p>0.31$). Correlation analysis was also used to investigate whether absolute error was related to time. Several parameters of interest varied with time during the field test which lasted from October 19 to November 11. These included cotton conditions, cotton moisture content, and equipment wear. Cotton conditions changed due to aging and weathering. Cotton moisture content was not measured, but a noticeable increase was observed during the late days of the harvest season. Equipment wear included several factors, most notably debris build-up on sensor lens covers, as lens covers were not cleaned during the harvest season. No statistically significant correlation between time and absolute error was present in the data set ($r=-0.11$, $p>0.34$).

Gin Testing

A second version of the system was installed on a pneumatic seed cotton conveying unit at the USDA-ARS Southwestern Cotton Ginning Research Laboratory in Mesilla Park, NM. A single duct conveyed the cotton, and one sensing unit was mounted on the duct.

System parameters were set as follows. A single sensing unit with seven emitter-detector pairs was used. The integration interval was 25 ms. The number of samples compared to obtain a baseline was 80, hence the baseline was reset every two seconds. The baseline offset was set at 10. The exponent, u, the weighting coefficients, C_i, and the scaler, K, were all determined through calibration.

Sixty loads of cotton were passed through the system, but data from one load was lost, leaving a data set of 59 loads. Two machine picked varieties (Upland DP 90 RR and Pima S 6) at two moisture contents (approximately 6.3 and 12.6 percent, dry basis) were used. Five loading rates (1, 2, 3, 4, 5 bales/hr) were randomized within each moisture content and variety block, and the experiment was replicated three times. Total load weights ranged from 420 to 625 lb with average cotton flow rates up to 2.6 lb/sec.

Data from the first ten loads was used to calibrate the flow prediction model. This set contained one load from each target flow rate at each moisture content.

The model was calibrated as follows. First, the exponent, u, was determined through iteration. Values for u were bounded by 1.0 and 2.0 with an iterative step size of 0.05. The optimum exponent was defined as that which resulted in the greatest coefficient of determination between integrated sensing unit outputs (integrated over load run times) and measured load weights. After the optimum u was found and applied, weighting coefficients, C_i, were determined in a similar manner. Values of C_i were bounded by 0.1 and 1.0, and a step size of 0.1 was used. Finally, the value of the scaler, K, was determined through least-squares linear regression.

As with the harvester data, parameters were applied to the model for flow rate calculation in the remaining 49 loads. Estimated flow rates were integrated over run times to generate predicted load weights. These were compared with actual load weights to quantify system performance.

The error distribution for the 1999 gin test is shown in Figure 5. The system predicted load weights to within ±10 percent for all but one of the 49 loads. The average absolute error was 3.4 percent. Correlation analysis was used to determine whether moisture content or average flow rate had any effect on absolute error. No statistically significant correlation between moisture content and absolute error was measured ($r=-0.144$, $p>0.32$). A statistically significant correlation between average flow rate and absolute error was observed ($r=0.507$, $p<0.05$). Figure 6 graphically illustrates absolute error as a function of average flow rate. Analysis of variance was used to determine whether variety had an effect on absolute error. A statistically significant effect was present ($p<0.05$). Mean separation of absolute error by variety was performed using the least significant difference technique ($\alpha = 0.1$). The mean absolute error for the Pima variety (S 6) was 2.4 percent, which was significantly less than 4.9 percent which was the mean absolute error for the upland variety (DP 90 RR).

Conclusions

A system for measuring cotton flow rate in real time has been designed and tested in two environments. When implemented on a harvester, the system measured total load weights to within ±10 percent for 75 of 79 test loads. The average absolute error for the 79 loads was 4.7 percent. When tested in the gin, similar results were obtained. Forty-eight of 49 total load weights were measured to within ±10 percent of true values. The average absolute error for the 49 gin test load weight predictions was 3.4 percent. Measurement accuracy was independent of average flow rate in the harvester test, however gin test results indicated a significant correlation between average flow rate and absolute error. This is not surprising since maximum flow rates in the gin test were much greater than those in the harvester test. Moisture content had no detectable effect on accuracy in the gin test, but variety did. Average absolute error was 2.4 percent for the Pima variety (S 6) and 4.9 percent for the upland variety (DP 90 RR).

Gin test results also suggest that for a given duct geometry and conveying air velocity, a maximum flow rate exists beyond which measurement accuracy will degrade. More tests would be necessary to define the relationship between air velocity, duct geometry, and the maximum measurable flow rate. Results indicate that cotton variety, or properties related to variety, also affect sensor performance.

The technology described herein has been patented (Wilkerson et al., 1999) and licensed to industry for application on mobile equipment. Future work may include additional data collection to more thoroughly define relationships between sensor performance and related variables, as well as system optimization for fixed applications, such as cotton flow measurement in the gin.

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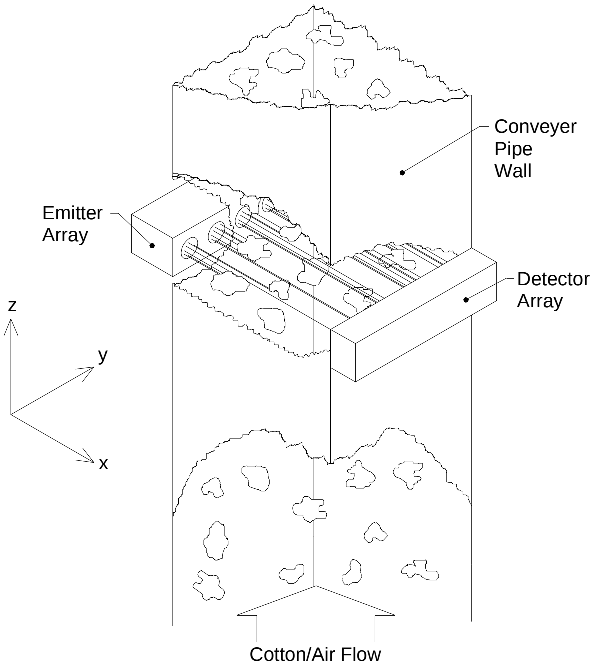
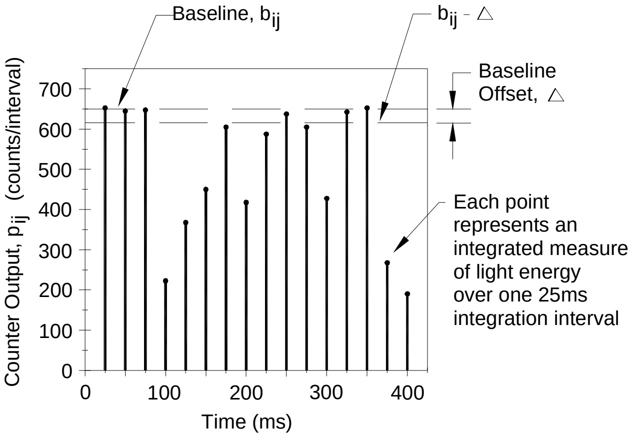
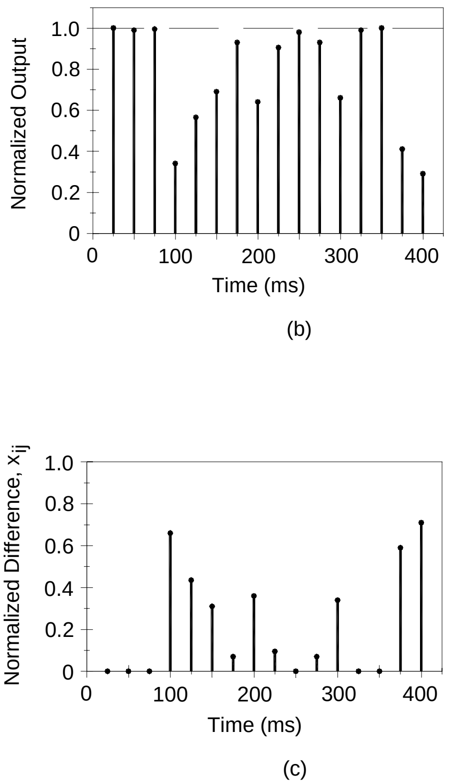


Figure 1. Cut-away view showing a mounted sensing unit



(a)



(b)

(c)

Figure 2. Graphs illustrating data processing steps. (a) Raw counter output, (b) normalized counter output, and (c) normalized difference.

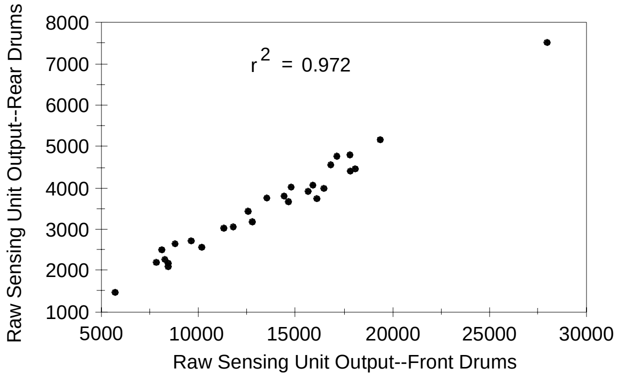


Figure 3. Relationship between outputs from sensing units on pipes serving front and rear picking drums.

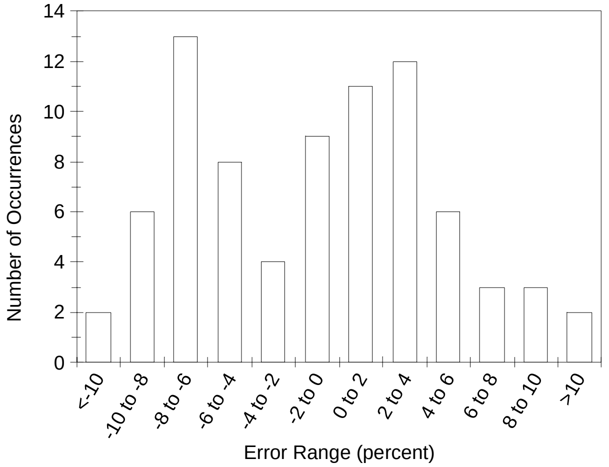


Figure 4. 1997 harvester test error distribution for 79 loads.

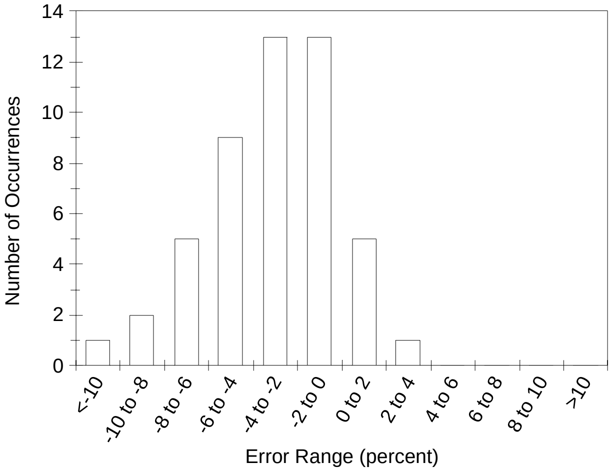


Figure 5. 1999 gin test error distribution for 49 loads.

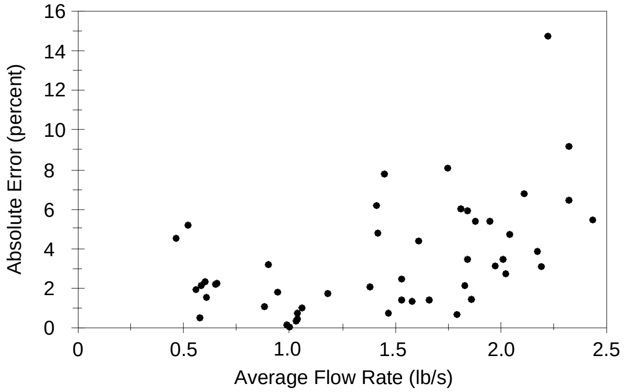


Figure 6. Absolute error as a function of average flow rate.