Development of an Electronic Hopper Weight Scale

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Abstract.
An electronic hopper weight scale was designed and built to measure and record the mass flow of seed cotton, lint or lint cleaner waste. The measurement could be used in a feedback control loop to optimize the operations of the gin equipment which included the feed control, gin stand, and lint cleaners. The bottom doors of the electronic hopper scale were pneumatically controlled by a PC to collect and dispose of the cleaner waste. A PC based data acquisition and control application was developed to collect data from a low cost USB based A/D converter that sampled filtered and amplified signals from two S-type strain gages. Tests were conducted on the electronic hopper to verify its functionality and performance. The electronic hopper design and its control software achieved a target accuracy of ±5%.

Keywords. lint cleaner, weight measurement, mass flow, cleaner waste, strain gages, data acquisition and control.

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Introduction

As the ginning industry continues to consolidate, new gin plants are built bigger with better equipment and quality control processes. The challenge was reported by Byler and Anthony (1997) for online measurements and their roles in optimizing a ginning sequence. A ginning process control system has the potential to maximize profit for its ultimate customers, the producers. It must do so by balancing the bale quality and yield from a ginning process. The more the cotton is cleaned by lint cleaners, the better are the color and classing grade (Griffin et al., 1970). However, lint cleaners also induce more fiber damage in the cotton and shorten fiber lengths because of their aggressiveness. Short fibers lower yarn strength, increase mill waste, and create yarn imperfection (Griffin and Lalor, 1984). To perform the task of maximizing profits for the producers, the control system requires accurate online measurements of relevant information to make the correct decision in varying the ginning sequence. One of the desired feedback items is the quantity of waste produced by lint cleaners in real time. Lint cleaner waste, erroneously called motes by the industry, is produced by lint cleaners during the combing and cleaning of fiber. Lint cleaner waste is usually conveyed by air in a duct to a condenser or cyclone for disposal. Measurement of mass flow of agricultural product is not new and has been reported by Howard et al. (1993) for grain, and Wilkerson et al. (1994), Thomasson et al. (1997), Whitelock (1998), Thomson et al. (1999), and Funk et al. (2000) for cotton. Many of the approaches measured mass flow of cotton based on light attenuation of an optical device. Wilkerson et al. found that accuracy of their optical device was sensitive to flow rate and cotton variety. Whitelock reported the importance of sensor calibration. Thomson et al. related the attenuation of light to the mass flow of lint cleaner waste. The relationship was a Weibull function based on measured voltage differences. Funk et al. (2000) estimated mass flow of seed cotton to ± 10% accuracy based on air pressure differentials in a vertical pipe.

The objective of this study was to develop a mass flow meter for measuring lint cleaner waste in real time with an accuracy of ±5%. The approach adopted in this study was based on an actual weight measurement using load cells because of its proven reliability and cost. Such a device could be adapted from commercially available seed scales, such as the LEC-100 by Lubbock Electric Co (Lubbock, TX). Since commercial units were served by proprietary software, it would be difficult to integrate such a closed system into our ginning process control system. It was then decided to build a new system based on a laptop PC with an inexpensive data acquisition software and hardware.

Materials and Methods

A weight scale based on the measurement of two S-type strain gages (LC101-25, Omegadyne, Inc., Sunbury, OH) was designed and built (figures. 1-2). The scale was built on a hopper with dimensions of 35.6 x 35.6 x 36.8 cm (14.0 x 14.0 x 14.5 inches, W x D x H) and was fabricated from 0.16 cm (22 gage) sheet metal. The hopper was suspended from a sturdy frame by one weight counter balancing spring on one side and two S-type strain gages at the corners on the opposite side. Two movable doors were made to enclose the bottom. The doors were operated by a pneumatic cylinder attached to the front side of the hopper. The seven-inch-stroke cylinder was controlled by an electric (Alternating Current) solenoid and a laptop PC. The sturdy frame was 1.4 m (4.5 ft) high and placed on casters for mobility. The lower section of the supporting frame was enclosed on three sides and the bottom to form a catch pan. The bottom of the catch pan was tilted at a 45 degree angle to the open front to ease material flow and retrieval. A Data Acquisition and Control Software (DACS) was developed to record the strain measurements, convert them to proper weight measurement units, and control the movement of the hopper doors at a predetermined weight limit (figure 3). The DACS was developed based
on an object oriented graphical development software package (Softwire ®) provided free by Measurement Computing Corporation (MCC, Middleboro, MA). The package itself was based on Microsoft’s .NET development platform and the graphical programming language, Visual Basic. In summary, the electronic hopper weight scale system consisted of the following components:

- a mobile sturdy supporting frame
- a hopper with actuated doors
- a pneumatic cylinder (047-D, Bimba Manufacturing Company, Monee, IL)
- a weight counter balancing suspension spring
- two vibration air-pot dampers (2KS56, Airpot Corporation, Norwalk, CT)
- two strain gages suspended at the corners (LC101-25, Omegadyne, Inc., Sunbury, OH)
- an instrument grade amplifier (gain of 200 X) and signal conditioning circuitry
- an A/D converter with digital output (PMD 1208FS by MCC)
- a laptop PC (Latitude CSx, Dell, Austin, TX)
- a DACS software package developed in-house using a commercial development package (Softwire ®, MCC)

Additionally, one table top and one platform scale were used in the experiments to serve as the basis for the weight measurement comparisons and accuracy assessment. The table top scale, Precisa 900C-3000 D (Zurich, Switzerland), had a specified accuracy of ± 0.1 g and the Sauter E1200 platform scale (Ebingen, Germany) had a specified accuracy of ± 0.1 kg.

Figure 1. A frontal view of the electronic hopper scale.
Figure 2. A close-up view of the electronic hopper scale showing the counter balancing spring and one of the two suspending strain gages.

Figure 3. Electronic hardware for DACS (Data Acquisition and Control Software).
Hopper model and analysis

Because of the symmetry of the electronic hopper, it can be modeled in 2-D as shown in figure 4. From the figure, the sum of forces in the vertical y direction and moment about O give:

\[ \sum f_y: F_s + F_{g0} = W_h \]  \hspace{1cm} (1)

\[ W_h = W_l + W_r \]  \hspace{1cm} (2)

\[ \sum M_o: W_l \cdot a = b \cdot W_r + c \cdot F_{g0} \]  \hspace{1cm} (3)

When material is put into the hopper for weighing, equation 3 becomes:

\[ \sum M_o: W_l \cdot a = b \cdot (W_r + W_m) + c \cdot F_g \]  \hspace{1cm} (4)

where:
- \( F_s \): spring force
- \( F_{g0} \): reaction forces measured by the strain gages when the hopper is empty
- \( W_h \): weight of the empty hopper
- \( W_l \): weight of hopper on the left side of spring
- \( W_r \): weight of hopper on the right side of spring
- \( W_m \): weight of the content in the hopper
- \( F_g \): reaction forces measured by the strain gages
- \( a, b, c \): moment arms to the respective forces from O

By combining equations (3) and (4), the weight of the hopper content can be calculated according to equation 5 below:

\[ W_m = -\frac{c}{b} \left( F_g - F_{g0} \right) \]  \hspace{1cm} (5)

Equation 5 is the governing equation for the electronic hopper scale. In practice, \( F_{g0} \) is measured electrically through a calibration procedure with an empty hopper, and equation 5 becomes:

\[ W_m = k_c * k_g * k_a * k_v \cdot (v_0 - v_{offset}) \]  \hspace{1cm} (6)

where:
- \( W_m \): weight of material (in desired engineering units)
- \( k_c \): calibration constant
- \( k_g \): strain gage factor, 10.25 lbs/0.0125 v
- \( k_a \): amplifier gain (200)
- \( k_v \): voltage range selection (+1.25 v / 2048 counts)
- \( v_0 \): average of the 2 strain gages output voltages in counts
- \( v_{offset} \): initial output voltage from the strain gages in counts when hopper is empty
Electronic Hopper dynamics

The static analysis presented above provided the measurement principle that determined the weight of the material contained in the hopper. However because the hopper was suspended and counter balanced by a spring and two strain gages, it was an active dynamic system. Its dynamic characteristics must be assessed because the electronic hopper, in addition to being subjected to ground vibration excitation, was also subjected to dynamic excitations stemming from the actuation of the pneumatic cylinder in opening and closing the hopper bottom doors. The natural frequency of a suspended mass system is calculated according to equation 7:

\[
\omega_n^2 = \frac{ks}{M} \quad (7)
\]

\[
\omega_d^2 = \omega_n^2 \times (1 - \zeta^2) \quad (8)
\]

\[
\zeta = \frac{c}{cc} \quad (9)
\]

\[
cc^2 = 4 \times ks \times M \quad (10)
\]

where

- $\omega_n$ = natural frequency of the hopper (rad/s)
- $\omega_d$ = damped frequency (rad/s)
- $\zeta$ = damping factor = 0.183
- $ks$ = spring rate of the suspending spring (4.4 N/mm or 25 lb/in)
- $M$ = suspending mass (13.2 kg or 29 lb)
- $c$ = damping (0.09 N*s/mm or 0.5 lb*s/in)
- $cc$ = critical damping (0.48 N*s/mm or 2.74 lb*s/in)
Based on the weight of the empty hopper, the natural frequency of the electronic hopper was calculated to be 18.25 rad/s or 2.90 Hz and the damped frequency was 2.86 Hz. The hopper gained a maximum of 0.91 kg (2.0 lb) of gin trash when filled. The natural and damped frequencies of the filled hopper were 2.81 and 2.77 Hz, respectively.

**Software implementation**

The DACS was developed based on the graphical programming software, Softwire® from MCC. To acquire signals from external devices, a built-in AIScan module from Softwire® was used. The module included the controls of sampling frequency, number of channels, and the scaling of sampled voltages to raw counts. All calculations in the program were based on count units; they were only converted to engineering units at the very end of the calculation to preserve precision. The DACS was written in an object oriented style and the relevant major functions implemented for the application included:

- calcAvg = computes averages of input channel signals
- LowPass = a 2-pole low pass filter
- RolAvgCalc = a rolling averaging filter
- Truncate = a bit masking function to reduce signal noise
- Calibrate = performs an empty hopper calibration procedure
- setDO = sets PMD1208FS’s digital output port to open and close doors

Major modules deployed from Softwire’s® built-in functions (controls)

- AiScan = an A/D converter scanner, which sets range, frequency, and channel selection.
- AppendArray = adds columns of data and outputs a one or two dimension array
- DateTimePicker = outputs current time and date
- DOWriteByte = configures and sets value to a digital output port
- ExcelWrite = writes data to an Excel™ spread sheet.

A wiring diagram of DACS is depicted in Appendix A, figure A1.

**Calibration procedure**

The purpose of the calibration procedure was to determine the slope and the intercept of a linear function relating the weight of the material contained in the electronic hopper and output voltage produced by the strain gages, which were linear devices. The first step of the calibration process was to initialize the system with an empty hopper. This initialization captured the intercept and the initial offset value (voffset) in counts. A known weight of 556.0 g (1.225 lb), which was predetermined by a precision (+0.1 g) table top scale, was put in the hopper to determine the slope (kc) of the function. The model equation for this relationship was written in equation 6. All conversion constants were known, except for kc. When the known weight was put into the hopper to weigh, it was sensed by the two strain gages, which sent their signals to an amplifier and an A/D converter in separate channels. The 12-bit A/D converter (PMD1208FS) in turn converted the signals into counts. These counts were averaged, filtered by a rolling average filter and substituted into equation 6 as v0. A trial kc value was put in the equation to calculate the weight of the hopper’s content in engineering units. The calculated value was output to the screen of a laptop PC and displayed. A final calibration constant (kc) was attained when the display value on the computer screen matched the value of the calibrating weight within a desired accuracy.
**Electronic hopper in operation**

To operate the electronic hopper, DACS was first compiled and executed. The electronic hopper was then initialized with an empty hopper. When the Zero and Start buttons on the screen of the electronic hopper user interface were pressed, the weight of the empty hopper was zeroed out electronically. Analog signals from the strain gages were amplified, filtered and digitized by an A/D converter into raw counts, which were sampled by DACS at a pre-selected frequency (1000 Hz). The sampled raw counts became the voffset used in equation 6. The initialization was completed in less than three seconds and the electronic hopper was ready to receive its first batch of material. As the material being weighed flowed into the hopper, the weight of the hopper rose and eventually exceeded a preset threshold level indicating a filled hopper. The electronic hopper was then triggered to open its doors and dispose of its content; by operating the electronic hopper in this manner, the hopper could be used to capture and record weights of cleaner waste in batches. The weight of each captured batch and a running total of weights in engineering units for the batches were recorded.

Two experiments were selected to be presented in this report to illustrate the performance and accuracy of the electronic hopper weight scale.

**Test 1.**

The test required a calibration of the hopper with a known weight and repeat measurements of the known weight in a manual mode. The known weight was determined by a precision table top scale (Precisa 900c-3000d).

**Test 2.**

This experiment included the blocking of the chute to stop material flow when the hopper was filled. The experiment included two levels of feed rates and two levels of thresholds that controlled the movement of the electronic hopper doors. The experiment was set up as a randomized complete block of 12 runs with three replicates. Based on observations from other experiments, the software, DACS, which controlled the electronic hopper, was modified to achieve more stable readings (see discussion). Material from each captured batch was collected and weighed individually on the platform scale (Sauter, E1200). The procedure generated 120 pairs of weight measurements from the 12 run experiment. The weight of each captured batch and a running total for the weights of the batches in a run were recorded by DACS in a file.

**Calculation and analysis**

The accuracy of the electronic hopper weight scale was assessed by comparing the electronic weight measurements against those determined by a platform scale. A percent weight difference was calculated by subtracting the electronic weight measurement from that by a platform scale, divided by the platform scale reading and multiplied by 100%.

In Test 2, in addition to calculating a percent weight difference for each batch, an average percent weight difference for a run (10 batches) was also calculated. Thus, the percent weight difference measured variability of the weight measurements between runs. Its variance was analyzed to determine the significance of the treatment factors examined in the experiment. Statistical analyses were based on Proc Anova and Proc Mixed by SAS (version 9.1, Cary, NC). Proc Mixed was developed based on Mixed model analysis (Littell et al., 1996). Means comparisons were based on Least Square Difference (LSD) calculations in SAS.
Results

Results of Test 1: Calibration with a known weight

Table 1 summarizes results of the 20 trial measurements after the electronic hopper was calibrated. It shows that the calibration was on target and matched the value of the known weight on average, with a standard deviation of 0.019 kg or 0.042 lb (2.96%). It was noted that the variances between the two sensors (S0 and S1) were very different due to a low value (origin unknown) obtained for S0 in run 1. If run 1 of S0 was eliminated, variances between the sensors would be comparable.

Table 1. Statistics of data from calibration runs with a known weight (0.65 kg) in Test 1.

<table>
<thead>
<tr>
<th></th>
<th>Weight recorded by electronic hopper, kg</th>
<th>S0, counts</th>
<th>S1, counts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>0.65</td>
<td>2368.55</td>
<td>2466.2</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.0190</td>
<td>44.262</td>
<td>4.073</td>
</tr>
<tr>
<td>Minimum</td>
<td>0.60</td>
<td>2181</td>
<td>2456</td>
</tr>
<tr>
<td>Maximum</td>
<td>0.67</td>
<td>2385</td>
<td>2472</td>
</tr>
<tr>
<td>Confidence level</td>
<td>0.0089</td>
<td>20.7151</td>
<td>1.9062</td>
</tr>
</tbody>
</table>

Results of Test 2.

The primary objective of the test was to verify that the modified software accurately weighed the cleaner waste captured in each batch. The experiment incorporated a chute blocking step during hopper door movements. An ANOVA of the total percent weight differences for the 12 runs showed that the accuracy of the weight measurements was not affected by feed rates and threshold limits. The average percent weight differences were encouragingly low (table 2). A statistical analysis performed on the averages of percent weight differences indicated that the mean of the percent weight differences between measurements by a platform scale and those by the electronic hopper scale was +0.45% with a standard deviation of 1.9%. The standard deviation of percentage weight differences on all 120 batches was + 4.5%. Thus, the experiment verified that it was necessary to repeatedly read the hopper weight measurement while the material flow was blocked. The modification in the software was necessary and made a significant improvement in accuracy for the electronic hopper scale. The latest software enhancement was responsible for bringing the mass flow measurement system to within the target accuracy of ±5%.

Figure 5 plots the weight measurements recorded in Test 2 by the electronic hopper (dependent variable, y axis) and the platform scale (independent variable, x axis). These data yielded a regression equation with a slope of 1.0045 and an adjusted $R^2$ of 0.9793. Figure 6 depicts the accumulative weights for the 10 batches in a run as measured by the electronic hopper and the Sauter-E1200 platform scale. The slope of the regression equation for the accumulative weight measurements was 1.0041 with an adjusted $R^2$ of 0.9891. The fact that both the $R^2$ and the slopes of the two regression models were close to unity showed that electronic hopper was measuring accurately with the software modification.
Table 2. ANOVA summary of Test 2a

<table>
<thead>
<tr>
<th>Source of variance</th>
<th>Average weight difference, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed rate</td>
<td></td>
</tr>
<tr>
<td>107 kg/m/hr</td>
<td>1.28 a</td>
</tr>
<tr>
<td>187 kg/m/hr</td>
<td>-0.37a</td>
</tr>
<tr>
<td>Limit</td>
<td></td>
</tr>
<tr>
<td>0.41 kg</td>
<td>1.07a</td>
</tr>
<tr>
<td>0.57 kg</td>
<td>-0.17a</td>
</tr>
</tbody>
</table>

*Means followed by the same letter is not significantly difference at p=0.05*
Discussion

From the static testing in Test 1, it was shown that the electronic hopper scale was capable of measuring material with an accuracy of +3.0%. When the scale was subjected to other dynamic tests, it exhibited poor accuracy and a constant positive bias.

By re-analyzing the segment of code that controlled the hopper door movements, it was found that the doors were triggered to move at any weight that exceeded the preset threshold value. The instantaneous weight could exceed the threshold by 1% or 10%. There was no de-bouncing logic to stabilize the door movement trigger. More importantly, because the electronic hopper scale was a dynamic instrument, it could benefit from a few more reading cycles of the weight after a threshold limit was exceeded to achieve a more stable weight reading for the batch. Thus the code was modified to block the chute when the hopper was filled. It also included a delay for additional scale reading cycles immediately before the doors were activated. It was this enhancement that brought about the accuracy improvement reported in Test 2.

The measurement cycle began from the moment the chute was unblocked, followed by filling the hopper in 5 seconds, depending on feed rates and processing the strain-gage signals (modified to extend the reading period to 8 seconds). The measurement cycle continued with the opening and closing the hopper doors in 2 seconds and ended with unblocking the chute again in 3 seconds. The electronic hopper also measured vibration in the background due to machinery running in the Microgin. The magnitude of the vibration was +0.03 kg at frequencies much higher than the resonant frequency of the hopper. This background vibration did not interfere with the measurement accuracy, because it was included in the initial calibration signals and subsequently subtracted from the weight measurements. The motions caused by the actions of the pneumatic cylinder in opening and closing the hopper doors also did not interfere with the accuracy of the weight measurement, because vibrations occurred after DACS had completed reading the weight in the hopper and were damped out by the time the next measurement cycle began again in 18 to 25 seconds depending on feed rates.

Conclusion

An electronic hopper weight scale was built and developed. A data acquisition and control application was written to collect and tally weight data in batches. Five separate tests were conducted to assess the accuracy and performance of the electronic hopper scale. In Test 1, the hopper scale achieved a +3% accuracy in a static test calibrated with a known weight.

By blocking the material flow during the measurement cycle and modifying the software to extend the reading cycles before door movements, the electric hopper achieved the target measurement accuracy of +5% in Test 2. The actual mean difference achieved by the electronic hopper from run to run in Test 2 was +0.45% with a standard deviation of +1.98%. The standard deviation for batch to batch variation was +4.63%. The slopes for the regression equations between weights measured by the electronic hopper and those by the platform scale were very close to unity. The slope was 1.0041 for the ten batches in a run and 1.0049 for the accumulative weights of the batches in a run. Adjusted R² for both equations were greater than 0.98.

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References


