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Abstract. *Due to the importance of yield monitoring, researchers have been developing systems for crops such as tomatoes, forage, sugar cane, citrus, and coffee. A yield monitoring system for pull type dry edible beans harvester has not yet been developed. The goal of this project was to design and test a drive torque measurement device on a clean grain bucket elevator of a dry bean harvester, and evaluate its potential to be used as a mass flow sensor. Tests were conducted in the Yield Monitor Test Facility (YMTF) of University of Kentucky following the recommendation of ASABE Standard S578 (2007) The device was tested within the flow rate range of 0 to 3.4 kg/s. The largest flow rate errors were ±4.2% at 3.3 kg/s and ±4% at 1.6 kg/s. The average accumulated mass errors of the sensor were less than 3.1% and the maximum accumulated error was 4.9% at a flow rate of 1.8 kg/s.*

Keywords. *Mass Flow Sensor, Laboratory Performance, Precision Agriculture, Yield Monitor, Edible bean harvester.*

Due to the importance of yield monitoring in agricultural management, researchers have been studying systems for crops such as tomatoes (Pelletier and Upahayaya, 1999), forages (Behme et al., 1997), sugar cane (Molin and Menegatti 2004), citrus (Schuller et al., 1999), and coffee (Balastreire et al., 2002). Systems for different crops might use different approaches for specific tasks, but they rely on the common concepts of measuring product mass flow rate, moisture content (when necessary), machine speed, and geographic position.

Dry edible beans are an important crop to many countries. Although dry edible beans can be harvested with conventional grain combines, the majority of this type of crop is harvested with specialized machines. Unfortunately, yield monitoring systems for specialized dry edible beans harvesters have not been developed.

Some dry bean harvesters employ a vertical bucket elevator that is mechanically powered by a drive chain to convey clean grain from the cleaning shoe to the clean grain tank. This elevator design makes it impossible to use currently available sensors for flow measurement. The relatively low speed of the elevators will not create a concentrated enough stream of grain with adequate velocity to allow use of the common impact plate flow sensors. The sides of the buckets will prevent use of optical sensors. Therefore, a new sensing technique must be developed for these machines.

After studying some of the sensing alternatives found in the literature, the option that seemed to be the simplest and easiest to implement on these machines was a rotary torque sensor on the elevator shaft, similar to Chaplin et al. (2004). Mundim (2003) developed and validated a power requirement model for a pull-type edible bean harvester with an axial threshing system that further validated this torque-sensing approach. The model for power estimation on the elevator shaft was based on the computation of the elevator chain tension using techniques outlined by the American Chain Association (ACA, 1975). The model was validated experimentally with a rotary torque sensor on the elevator power shaft. It was found that the power requirement of the bucket elevator under no load was 0.17 kW, whereas under field operation at maximum harvesting capacity of 5.5 t/h, the power requirement was 0.32 kW. The mass flow through the bucket elevator increased the power demand on the elevator shaft by about 88%.

Unfortunately, commercially available rotary torque sensors were too expensive to use on the relatively inexpensive harvesters. The alternative torque-sensing method considered in this study exploited the mechanical roller chain-drive on the elevator, where the tension on the roller chain should vary as the torque on the elevator shaft varies according to the mass flowing through the elevator. Thus, a force-sensing element such as a load cell on the tensioned side of the roller chain should correlate with the shaft torque and consequently to mass flow. The technique of sensing the force in the tensioned side of the drive chain has been applied by other researchers to measure quantities such as biomass on the combine header (Veal, 2006). The same technique was used by Silbernagel (1999) to control the expeller of a manure spreader. That, added to the work accomplished by Chaplin et al., (2004), Mundim (2003), and Hall et al. (2003) as well as the simplicity, ease of implementation, and low cost compared to the rotary torque sensor made this the chosen option. Further, preliminary

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bench test evaluation reported by Zandonadi (2008) supported the pursuit of this technique as a mass flow sensor alternative.

Objective

The goal of this study was to develop and test a torque measuring device as an alternative mass flow sensor for dry bean harvesters. The device was tested on a bucket-type clean grain elevator using the University of Kentucky's yield monitor testing facility to evaluate:

- calibration methods,
- sensor response to steady state flow,
- sensor response to dynamic flow changes, and
- sensor response to elevator tilt angle

Methods

Experimental Set Up

The new torque measuring device was a load cell-based mechanism (fig. 1). A 15-tooth idler sprocket (S2) was placed on the tensioned side of the #50 roller chain between the driver sprocket (S1) and driven sprocket (S3), which was attached to the elevator shaft. The idler sprocket was mounted on a 110-mm pivoting arm, and a 4.5-kN beam-type load cell was fastened behind the arm holding it against the roller chain. The torque developed on the elevator shaft, which was attached to the sprocket S3, was computed based on the force component (Fs) sensed by the load cell.

A bucket elevator from a dry bean harvester was donated by MIAC (Maquinas e Implementos Agricolas Colombo, Pindorama, SP, Brazil) to be used in the experiments. The flow sensing device was mounted on the elevator with a fabricated mounting flange (fig. 2) that was bolted through the elevator shaft bearing flange. This approach did not require modification of the elevator structure making it very easy to retrofit existing machines. Extension hubs were fabricated and placed on the end of each shaft to provide enough clearance for the sensor between the sprockets and bearing. Slots on the mounting flange permitted fine adjustment of sensor position. A magnetic sensor was mounted on the drive sprocket to monitor elevator speed.

The yield monitor testing facility (YMTF) was developed by Burks et al. (2003) at the University of Kentucky's

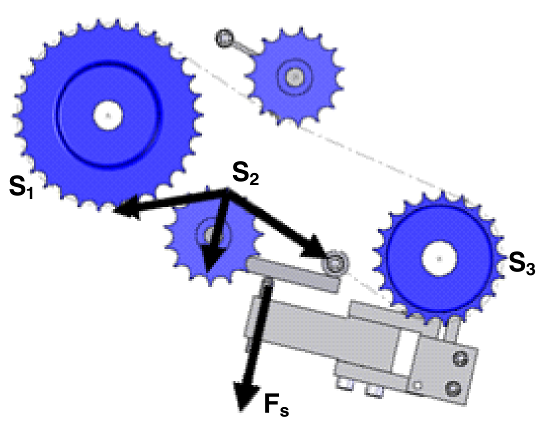

Figure 1. Schematic of the load cell-based mechanism evaluated for measuring torque on the elevator shaft.

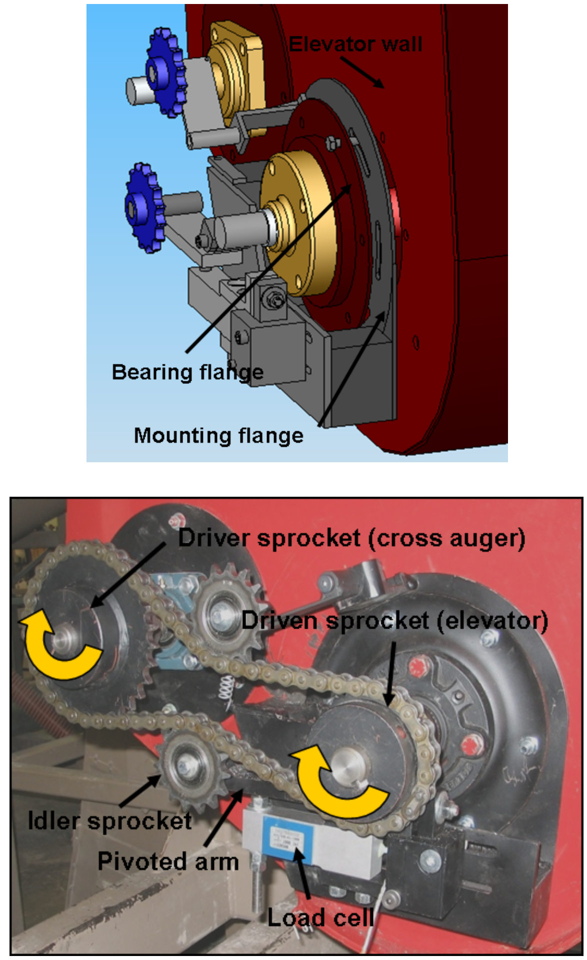

Figure 2. Sensor retrofitting mounting flange design and sensing device retrofitted on the elevator.

Biosystems and Agricultural Engineering Department. The facility is composed of two storage/supply tanks that hold up to 18 m^3 of grain, a volumetric grain metering device capable of varying the flow supplied to the clean grain elevator from approximately 0.4 to 31.7 kg/s, a fixture that supports the clean grain elevator and is capable of being tilted ±12° in the pitch and yaw directions, and a 15-kW hydraulic motor that drives the elevator.

The YMTF was controlled by a programmable logic controller using a User Interface Terminal (UIT) developed with Visual Basic. The UIT enabled the operator to select several options for controlling flow rates including automatic timed flow control where the operator specifies the duration and fixed flow rate to be delivered during the run, manual flow where there is no predefined runtime and the operator can change the flow rate during the run, and pattern defined flow where the operator can configure patterned flow for transient and oscillating flow testing.

Instrumentation

At the elevator shaft rated speed of 120 rpm, the 21 tooth driven sprocket and the 15 tooth idler sprocket (fig. 1, S2) were expected to generate a noise signal of approximately 42 Hz. Therefore, to prevent aliasing, a sampling rate of 200 Hz was chosen to collect the load cell output. The adequacy of that sampling frequency was validated in a preliminary study (Zandonadi, 2008). The data from the load cell were collected using a 12 bit A/D converter through a PCMCIA data acquisition card connected to a notebook computer. The magnetic sensor was connected to a 16 bit down counter of the DAQ board. The interface program written in VB.net with the UNIVERSAL LIBRARY was able to log the load cell output continuously at 200 Hz simultaneously with the speed sensor data. The output file also included the mass flow rate and accumulated mass calculated from the calibration parameters, shaft speed (rpm), number of observations streamed on the buffer, and load cell average voltage output.

Grain Material

Unfortunately, researchers were not able to procure dry edible beans in ample quantity to conduct the tests; therefore, soybeans and corn, which were more readily available, were used to test the sensor. Since the bulk density of soybeans and dry beans are similar (772 kg/m^3 according to *ASABE Standards* D241.4, 2007), the majority of the experiments (static and dynamic flow tests) were conducted with soybeans. Because of the bucket design of the conveyor, the material properties other than mass should not affect the drive torque since there is no friction of the grain along the side walls or other parts of the elevator. The only place where grain material will have an effect on drive torque is in the boot of the elevator where buckets engage the grain to scoop up their loads.

Experimental Procedure

Signal Conditioning and Sensor Response

The data used in the analyses were recovered from the stored files generated during the experiments using a program written in MatLab (The Mathworks, Natick, Mass.). The software (fig. 3) recovered the raw data and allowed the user to control the filtering and calibration parameters as well as the data output rate of the processed data.

A moving average filter was used to smooth the raw sensor signal to facilitate identification and investigate undesired trends in the signal. Then, the smoothed data were further processed and quantized by averaging every 100 data points to produce processed flow data at 2 points/s. In general, the 2 data points/s processed profiles were used for subsequent analyses.

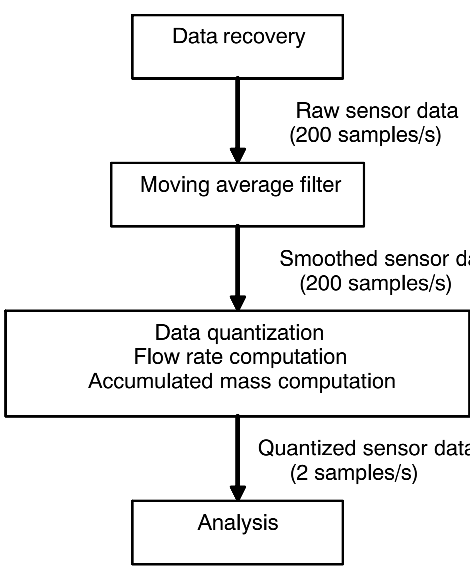

Figure 3. Flow diagram of the computational tasks executed by the data recovery program.

Calibration Methods

The device was calibrated dynamically and statically. The purpose of executing both methods of calibration was to investigate the possibility of eliminating the need for dynamic calibration in the field using weigh wagons or scale tickets. The hypothesis was that if there is a relatively stable relationship between mass flow rate and torque on the transmission, mass flow could be computed based on a static calibration for torque measurement.

The dynamic calibration was accomplished by running a set of known flow rates through the elevator. The volumetric flow controller of the laboratory test facility was able to deliver flow rates from 0.4 to 31.7 kg/s, in steps of approximately 0.4 kg/s. Considering an average crop yield of 1800 kg/ha and typical harvesting capacity of 4.5 ha/h, an average grain flow rate of 2.25 kg/s should be expected at the clean elevator. Thus, the testing facility had adequate capability to supply a reasonable range of grain flow rates for the experiments.

The actual reference flow rates were based on the accumulated mass in the weigh tank after each run. Calibration data were evaluated by using a linear regression on the sensor calibrated data against the reference mass flow, and then applying a t-test with the null hypotheses that the regression slope was equal to one (Ho: $\beta o = 1$ vs. Ha: $\beta o \neq 1$) and the regression intercept was equal to zero (Ho: $\alpha = 0$ vs. Ha: $\alpha \neq 0$).

The static calibration was accomplished by physically locking the elevator shaft and installing a moment arm on the driver shaft so different torque levels could be created by hanging weights on the arm (fig. 4a and b). The procedure was repeated during the steady state and dynamic flow tests with soybeans. The moment arm was loaded sequentially, and for every load, data were collected for a period of 20 s at 1Hz. The moment arm loading procedure was repeated three times during calibration. Once the torque calibration was completed, the lock and moment arm were removed.

The amount of torque to be applied during static calibration was computed to correspond to the expected flow rates in the conveyor as outlined by the American Chain Association (ACA, 1975) in the following equations.

$$T_{el} = k_1 + k_2 \cdot Q_g \quad (1)$$

$$k_1 = \left(m_{ch} \cdot h + m_{bu} \cdot n_{bu}\right) \cdot g \cdot r \quad (2)$$

$$k_2 = \left[60000 \cdot \frac{h}{N_t \cdot p \cdot n}\left(1 + \frac{1}{n_{bu}} \cdot \frac{12 \cdot J \cdot d}{e_c}\right) \cdot FS\right] \cdot g \cdot r \quad (3)$$

where

Q_g = mass flow rate (kg/s)
m_{ch} = linear mass of the chain (kg/m)
m_{bu} = mass of a individual bucket (kg)
n_{bu} = number of buckets in on side of the strand
g = gravitational constant (m^2/s)
h = distance between top and bottom elevator axles (m)

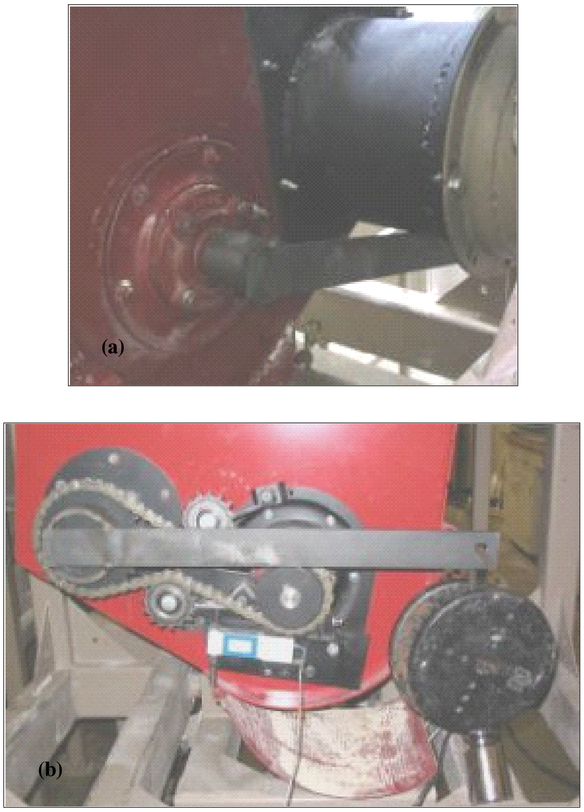

Figure 4. Static calibration apparatus. Lock arm (a) and moment arm (b).

r = distance of the force application point in elevator chain and the elevator shaft (m)
N_t = number of teeth of the boot sprocket
p = chain pitch (mm)
n = boot sprocket speed (rpm)
d = diameter of the boot sprocket (m)
e_c = bucket spacing (m)
J = empirical corrective factor
FS= service factor

J and FS are empirical parameters in the model. ACA (1975) recommends a J value of 1 for centrifugal discharge elevators handling coarse lumpy material, 0.67 for centrifugal discharge elevators handling fine free flowing material, and 0.5 for continuous bucket elevators. FS is defined according to the speed and service conditions (shock, type, and frequency of operation, etc.) and varies from one to three.

Once the system was calibrated for torque, mass flow rate going through the elevator was computed based on the rearranged torque equation 4 and it was compared with the measurements based on the dynamic calibration.

$$Q_{gb} = \frac{T - k_1}{k_2} \qquad (4)$$

where
Q_{gb} = torque based mass flow rate (kg/s)
T = torque measured by the device (Nm)

Steady State Flow Test

Steady state tests were accomplished by running constant flow rates of grain within the elevator's capacity range for a period of 2 min while recording data from the reference (weigh tank) and the elevator mass flow sensor. The YMTF controller was set to 120 s of timed flow control and the elevator mass flow sensor data collection, on a separate computer, was triggered simultaneously with the mass flow start up. Following the recommendation of ASABE S578 Yield Monitor Performance Test Standard (*ASABE Standards*, 2007) the flow rates tested were approximately 50%, 75%, and 100% of the elevator capacity. The grain used in the steady state flow tests was soybeans at 9.5% moisture content, and every test was repeated three times.

Dynamic Mass Flow Test

The system dynamic performance was tested using ramped up-down, ramped down-up, and step flow patterns. The ramped up-down test started at 50% of the maximum flow capacity for 20 s before it was linearly increased to the full flow in 10 s. The maximum flow was held for 10 s, after which it was uniformly decreased to 50% of full flow in 10 s where it was maintained for 20 s before the flow meter was shut down. In the ramped down-up tests, the procedure was similar, except that the maximum flow rate was used as the starting point and the 50% rate as the midpoint flow.

In the step flow tests, grain flow was started at 90% of the maximum flow rate and held for 20 s. Then the flow was abruptly changed to different flow rates for a dwell period of 20 s each according to the following sequence: 50%, 90%, 75%, 90%, and 0% of the maximum flow rate. The grain used was soybeans at 9.5% moisture content, and every test was repeated three times.

Tilt Test

The tilt test was conducted by tilting the whole fixture forward and backward approximately 6° with respect to its vertical axis, which would be analogous to a field slope of 10.5%. At each position, the target flow rates of 1.8, 2.7, and 3.6 kg/s were evaluated. Each flow rate was repeated three times. The average percentage error of the accumulated mass measured by the sensor was computed using the weight tank as a reference. The test was accomplished using soybeans and corn at 9.5% and 14% moisture content, respectively.

Elevator Speed

The target elevator speed was 120 rpm, but the elevator speed varied slightly in accordance with the grain flow rate. To remediate this issue, the speed was compensated by changing the drive motor hydraulic flow rate for each mass flow rate of grain in the steady state flow tests to keep the shaft speed at 120 ± 3 rpm. Unfortunately, this compensation was not possible for the dynamic flow rate tests. In these tests, the hydraulic flow rate was set to provide a speed of 120 ± 3 rpm near the maximum capacity, which resulted in a slightly higher elevator speed for all dynamic tests with the maximum speed of 129 ± 3 rpm for zero flow.

Results and Discussions

Signal Conditioning and Sensor Response

The sensor output at different flow rates showed that the sensor responded properly up to 3.4 kg/s flow rate (fig. 5). The oscillating performance at 0.4 kg/s was a consequence of surging flow from the YMTF flow controller. It was possible

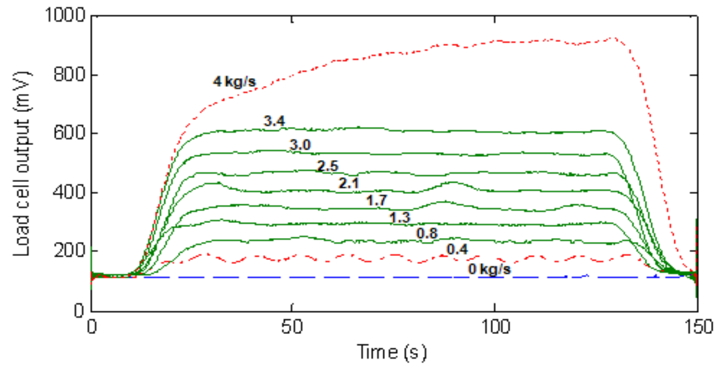

Figure 5. Sensor output profile according to the mass flow filtered by a 4-sd moving average.

to observe that there were periods that the buckets were completely empty. Thus, the flow rate of 0.4 kg/s was discarded from further evaluations due to limitations of the YMTF. The ramp profile at 4 kg/s was a result of overloading of the elevator. At this flow rate, the buckets were getting overfilled, and a grain build up was observed in the elevator boot. Because of the elevator capacity limit, subsequent tests were limited to approximately 3.4 kg/s when operating at the rated speed of 120 rpm.

The time delay for grain to travel from the meter of the YMTF to the elevator was found to be approximately 13 s, which was longer than the 8-s time delay reported by Burks et al. (2003) when using conventional grain combine elevators in the YMTF. The longer delay is explained by the lower rated speed of the cross auger that feeds the bucket elevator. On a grain combine, the cross auger shaft is typically the same shaft that carries the elevator's paddle chain, which often operates at speeds near 400 rpm. On the bucket elevator, the cross auger and the elevator's bottom shaft are connected by the drive chain (fig. 2). The speed ratio between the cross-auger and the elevator shaft resulted in a cross auger rated speed of approximately 87 rpm. Consequently, the meter to scale delay time was also longer.

Another difference between the conventional flow sensor and the new bucket elevator system was the sensor position. On a conventional combine, the impact plate is normally placed at the top of the elevator, and the time delay includes the time for grain to travel up through the elevator. With the experimental device, the mass flow starts to be sensed when the first bucket scoops grain at the elevator boot. The mass flow rate does not reach steady state until all buckets along the elevator chain are continuously filled with a similar amount of grain. Consequently, the time required to reach a steady state sensor output was relatively long.

Calibration Methods

Dynamic sensor calibration was accomplished by running a set of four different flow rates (0.9, 1.8, 2.7, and 3.4 kg/s) within the elevator capacity range. Four total calibration runs were used – one before and after the static and dynamic flow test sequences. The pre-test runs were used to calibrate the device; the post-test runs were used to check calibration. The linear regression coefficients and their respective intervals are presented in table 1.

The high coefficient of determination ($R^2 > 0.99$ for all runs) and the significance of the analyses of variance (P value < 0.0001 for all runs) strongly supported the linear relationship between Y and X, i.e. mass flow rate and sensor voltage output. Notice that the slopes of Run A and B fell into each other's confidence interval as well as the slopes of Run C and D forming two groups according to the shaft speed characteristics of each test. That showed that the curves could be considered similar among each group and that there was not a significant change in the device response across the experiments. The difference between groups was due to the fact that at a higher shaft speed, a lower torque is developed on the elevator shaft for the same mass flow rate. Consequently, the lower sensor response for the dynamic tests reflected the lower slope of curves C and D, which had the elevator's no-load shaft speed set to a higher value. Thereby, the Run A and Run C data were used to calibrate the system before the steady state and dynamic flow, respectively, and the Run B and Run D data were used to validate and assess calibration error for steady state and dynamic flow rates, respectively. The results of the t-test for calibration test are presented in table 2.

The P values for the slopes indicated that the slopes were well adjusted. The P value for the intercept indicated that it was different than 0. This intercept problem is indicative of a zero offset issue and could be minimized in practice by

Table 1. Regression coefficients of the calibration curves.

		95% Interval			95% Interval	
Run	Slope	Lower	Upper	Intercept	Lower	Upper
(A) Before steady state[a]	126.5	126.1	126.9	92.7	91.9	93.4
(B) After steady state[a]	126.6	125.9	127.3	89.3	87.9	90.6
(C) Before dynamic[a]	122.4	122.0	122.7	93.3	92.6	94.1
(D) After Dynamic[a]	122.6	122.1	123.0	94.7	93.8	95.5

[a] $R^2 > 0.99$ and P value < 0.0001.

Table 2. Results of the t test applied to the calibration verification with the validation data set.[a]

Group		Estimate	Standard Error	Test	P Value
Steady state calibration	Slope	1.00	0.003	0.35	0.729
	Intercept	-0.03	0.005	-5.09	0.000
Dynamic calibration	Slope	1.00	0.002	0.93	0.352
	Intercept	0.01	0.004	3.11	0.002

[a] Degree of freedom of 748, critical value of t = 1.963.

periodically measuring the no load output and resetting an offset point at the zero load. The zero load measurement check could be carried out, for instance, after unloading the harvester's basket or even during head land turn operations when there is no grain flowing through the elevator.

Static sensor calibration was accomplished by sequentially imposing a range of torques from 0 to 85 Nm on the elevator shaft, which corresponded to mass flow rates up to 6.0 kg/s. The device tended to respond differently during the first loading/unloading cycle of the moment arm than it did on subsequent cycles. Such behavior could be explained by the settling of the mechanism when the load was first applied on the system. That indicated that preloading was necessary to condition the mechanism. In practice, a calibration procedure could be specified to apply the necessary preloading before collecting calibration data. The calibration equations for torque versus estimated mass flow are presented in table 3 with 95% intervals for the slope and intercept.

The no-load reading was somewhat difficult to attain consistently. It was influenced by the positioning of the lock and moment arms and also the position in which the transmission was found when the arms were mounted. That is why the intercept presented such variation. The critical part of the investigation was the rate at which the sensor output changed relative to the torque input (mV/Nm), i.e., the regression slope. Thereafter, the dynamic torque would be computed by multiplying the sensor output, when subject to mass flow rates, by the slope resulting from the static torque calibration. The offset would be compensated with the periodic no-load adjustment mentioned earlier.

Combining the second and third repetitions of each static calibration cycle, a slope of 9.2 mV/Nm was computed, and it was used to convert the sensor readings into torque. Thereafter, given the torque measured by the sensor, the mass flow rates were estimated by recasting the torque model according to equation 4.

Table 3. Torque calibration regression parameters.

Tests[a]	Slope	95% Interval Lower	95% Interval Upper	Intercept	95% Interval Lower	95% Interval Upper	R^2
A	7.2	6.8	7.5	211.6	193.2	230.1	0.97
A	9.0	8.8	9.3	256.6	244.5	268.8	0.99
A	9.1	9.0	9.3	223.4	215.7	231.1	0.99
B	7.9	7.7	8.1	312.9	302.0	323.7	0.99
B	9.3	9.1	9.4	209.6	201.7	217.5	0.99
B	9.4	9.3	9.5	185.8	179.7	191.9	0.99

[a] Static torque calibration for steady flow tests (A) and static torque calibration for dynamic flow tests (B).

$$Q_{gb} = \frac{T - 9.7}{12.3} \quad (5)$$

where

T = torque measured by the device (Nm)

Q_{gb} = torque based mass flow rated (kg/s)

The mass flow rate computed from equation 5 was referred to as torque-based mass flow rate. The theoretical torque, which was computed from the ACA model (eq. 1) did not match exactly with the torque indicated by the sensor after it was calibrated using the static torque calibration technique (fig. 6).

Notice that the measured torque tended to be higher than the theoretical torque as the mass flow increased. If the torque model underestimates the measurement, the use of its parameters to compute mass flow rate will result in an overestimation of mass flow. By regressing the torque-based mass flow against the reference mass flow, it was possible to evaluate the overestimation caused by usage of the static calibration alternative. The regression results are presented in table 4.

For data sets A and B the elevator speed was compensated according to the flow rate keeping it at approximately 120 rpm throughout the calibration, whereas in data sets C and D, the elevator speed was not constant. The speed varied from 129 rpm (at 0 kg/s) to 120 rpm (at 3.3 kg/s). Thereby, it was expected that the data sets A and B would have presented better results than data sets C and D due to the fact that the parameters used in the theoretical torque model were computed based on an elevator speed of 120 rpm. However, the lack of specific recommendation for the empirical variables (J and FS) that describe the working condition and environment of the bucket conveyor on the harvester requires some adjustment in order to improve the performance of the theoretical torque model. This explains the drifting of the measured torque presented in figure 6. The parameter values used in the model were the same ones used by Mundim (2003), which were 1 and 1.73 for parameter J and FS, respectively. Changing the service factor (FS) from 1.73 to 1.93, improved the performance of the model (table 5).

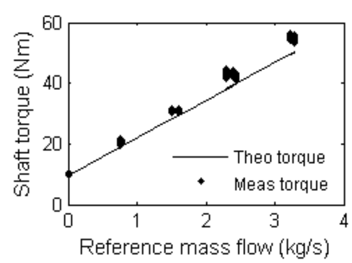

Figure 6. Theoretical (torque model) and measured (sensor) torque measurement vs. grain flow rate.

Table 4. Regression results of the reference mass flow rate vs. the torque-based mass flow rate.

Data Set	Slope	95% Interval Lower	95% Interval Upper	Intercept	95% Interval Lower	95% Interval Upper	R^2
A	1.120	1.114	1.127	0.013	0.000	0.025	0.99
B	1.116	1.112	1.121	0.031	0.023	0.040	0.99
C	1.076	1.072	1.080	0.060	0.052	0.069	0.99
D	1.077	1.072	1.081	0.042	0.034	0.050	0.99

Table 5. Regression results of the reference mass flow rate vs. the torque-based mass flow rate using a modified service factor in the torque model.

Data Set	Slope	95% Interval		Intercept	95% Interval		R^2
		Lower	Upper		Lower	Upper	
A	1.002	0.996	1.008	0.011	0.000	0.023	0.99
B	0.999	0.995	1.002	0.028	0.021	0.036	0.99
C	0.962	0.959	0.966	0.054	0.047	0.061	0.99
D	0.963	0.959	0.967	0.037	0.030	0.044	0.99

Notice that data sets A and B now presented better results than datasets C and D. Hence, the FS parameter should be refined for this type of elevator.

Another point of investigation would be the parameter adjustment according to the grain type. For instance, the slope obtained for 14% moisture content corn using the service factor of 1.93 was 1.018 (95% interval of 1.014 to 1.022), for elevator speed compensated according to the flow rate. Comparing this value with the slopes of A and B for soybeans (9.5% moisture content), it was clear that the slope was out of range and the parameters should be readjusted. However, once new parameters for different grain type and moisture contents are established, this alternative seems to be feasible for a simplified calibration approach.

Steady State Flow Test

As expected, the sensor output during the steady state test exhibited a great deal of noise, but the filtering techniques were successful in reducing that noise (fig. 7). Unfortunately, there was a great deal of noise on the weigh tank sensors as well. Even after smoothing the reference data with a 10-s moving average filter, it was still very difficult to use the data

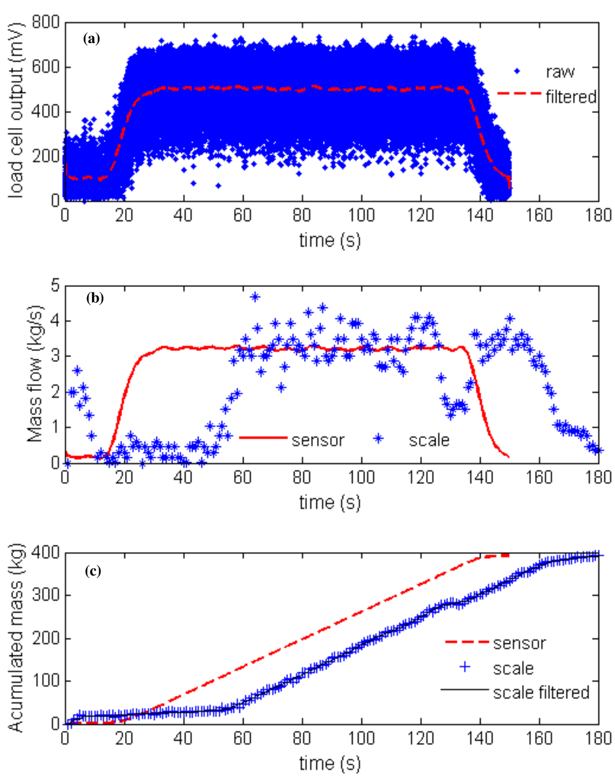

Figure 7. Sensor voltage output profile (A), sensor and reference scale instant mass flow rate measurement profile (B), and sensor and reference accumulated mass measurement (C).

for instantaneous mass flow rate computation. Burks et al. (2003) reported problems with the instantaneous flow rate measurement based on the weigh tank at flow rates of 1 to 2 kg/s. The authors pointed out that the grain stream dynamics, tank vibration caused by the grain pump, and load cell sensitivity were some possible causes of the variation of instantaneous flow rate measurement.

During the test, the data recording from the flow sensor was halted after the elevator was shut down by the YMTF base controller (around 150 s after the beginning of the test), but the weigh tank readings were recorded for an additional 30 s to compensate for the delay time. Although the accumulated mass seemed to be flattened at the end of the 180 s, data should have been recorded for longer period considering that the meter to scale delay time for this setup was considerably longer when compared to the setup for grain combine elevators (approximately 55 as compared to 40 s). This issue explains the presence of high flow rates and accumulated mass right at the beginning of the run caused by grain that was not completely emptied from the previous run.

Steady state sensor performance was evaluated by running two series of flow rates equivalent to 50%, 75%, and 100% of the elevator capacity, or 1.6, 2.5, and 3.3 kg/s, where each flow rate was repeated three times with a runtime of 120 s each. The actual flow rate was computed by dividing the accumulated mass in the weight tank at the end of each run by the duration of the runtime. The total accumulated mass at the end of each test was compared and errors were reported (table 6).

The accumulated mass for two different flow rates tested are presented in figure 8. The data were adjusted to compensate for the meter to scale delay time. The similarity of the weigh tank and the sensor slopes confirms the capacity of the sensor to measure flow rates. Note that the weigh tank data presented less instantaneous variation at higher flow rates; however, the step anomaly observed in the reference data, which was caused by an uncorrectable firmware glitch prevented detailed analyses of instantaneous data.

The grain flow rate of 3.3 kg/s caused the highest standard deviation (0.07) in the instantaneous flow rate measurement by the sensor. At a two SD level, the deviation at 3.3 kg/s was ±4.2% and the deviation at 1.6 kg/s was ±4%. The average accumulated mass errors were less than 3.1% and the maximum accumulated error was 4.9% at a flow rate of 1.8 kg/s. These results indicated that the sensor is a feasible tool to develop a relationship between yield maps and variable rate applications according to Howard et al. (1993), who suggested that the sensor should record data within ±5 to 10% of the actual grain weight.

Dynamic Mass Flow Test

The results of the ramp and step dynamic flow tests indicated that the mass flow sensor was able to detect changes

Table 6. Accumulated mass results during the steady state flow tests.

	Reference (weight tank)			Mass Flow Sensor			
Target Flow (kg/s)	Actual Flow[a] (kg/s)	Indicated Flow[b] (kg/s)	Total Mass (kg)	Indicated Flow[c] (kg/s)	Total Mass (kg)	Total Mass[d] Error (%)	Max Error[e] (%)
1.8	1.6	1.3 ± 0.8	188.1	1.5 ± 0.03	183.2	3.1	4.9
2.7	2.5	2.3 ± 0.7	285.1	2.4 ± 0.04	286.2	2.0	3.7
3.6	3.3	3.1 ± 0.6	391.6	3.3 ± 0.07	392.2	1.0	1.6
1.8	1.6	1.3 ± 0.8	194.1	1.6 ± 0.02	188.4	1.2	1.9
2.7	2.4	2.3 ± 0.8	296.9	2.4 ± 0.04	288.8	1.8	2.1
3.6	3.2	3.2 ± 0.7	391.5	3.3 ± 0.05	398.1	1.9	2.6

[a] Flow rate computed by dividing the total accumulated mass over the runtime period.
[b] Average of indicated flow rates of a 90 second period (90 observations) ± 1 standard deviation.
[c] Average of indicated flow rates of a 90 second period (180 observations) ± 1 standard deviation.
[d] Error (%) = |(sensor total mass - tank total mass)/tank total mass)| × 100.
[e] Maximum error found among the three repetitions.

in the flow patterns (figs. 9, 10, and 11). Unfortunately, weigh tank sensor noise at low flow compounded by the lack of reference from the flow meter controller hampered complete objective evaluation of the sensor response to dynamic mass flow and explanation of time anomalies presented in the data. Alternatively, the mass flow sensor data profile was compared to the expected target mass flow rate profile. This assumption was deemed reasonable to evaluate the potential of the sensor in dynamic flow measurement.

The sensor transient period led to a data smoothing of short transitions in the flow rate noted on the performance graphs. This smoothing issue could be a problem if the user desires to produce a pin-point yield map with high spatial resolution. However, edible bean harvesters typically pick up a windrow that was created by a wide windrower. In the case of the harvester and elevator used in this project, the windrow usually represents a width of 9 m. Considering a typical operating speed of 5.0 km/h and the sensor steady state response time of 13 s, the along-track resolution of the flow sensor would be approximately 18 m. Researchers have shown that currently available yield monitor systems cannot be expected to produce yield maps with relevant resolution

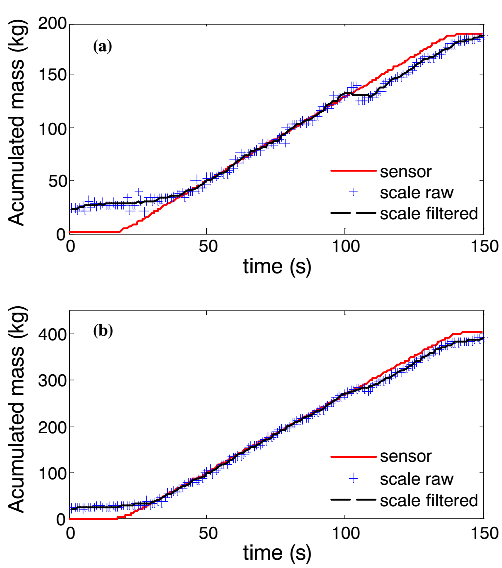

Figure 8. Accumulated mass profile of sensor and weigh tank for 1.6 (a), and 3.3 (b) kg/s mass flow rates.

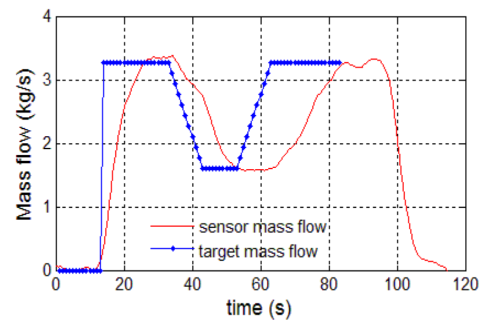

Figure 9. Sensor mass flow rate and target mass flow rate profile for ramp down-up transient flow sensor and expected mass flow rate profiles.

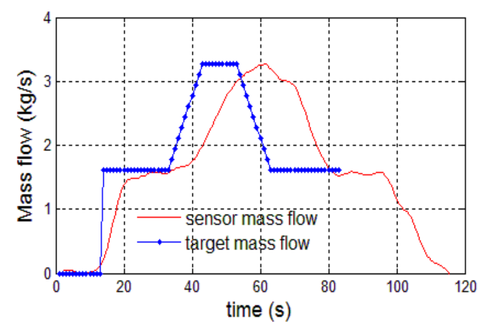

Figure 10. Sensor mass flow rate and target mass flow rate profile for ramp-up-down transient flow sensor and expected mass flow rate profiles.

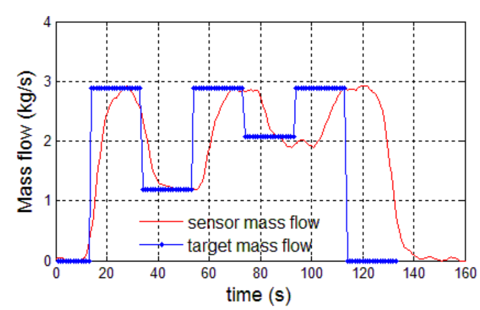

Figure 11. Sensor mass flow rate and target mass flow rate profile for the 20-period step flow experiment.

less than 15 m (Lark et al., 1997). Furthermore, Lamb et al. (1995) suggested that farming practice may require resolutions of no more than 60 to 90 m.

Tilt Test

Results from tilt tests using soybeans and corn are presented in tables 7 and 8, respectively. The elevator's tilt of 6° forward and backward with respect to its vertical axis corresponded to 10.5% ground slope. The data presented are the average of the total mass measurement error over the three repetitions from each target flow rate.

Notice that the errors for either forward or backward tilt were considerably higher than the errors at the vertical position, especially for the higher flow rate of the backward tests. The overestimated flow at the higher flow rate can be explained by the change of the effective volume of grain carried on each one of the buckets according to the angle. The volume of grain transported by each bucket in the backward position is smaller than the other two, and consequently, the grain build up in the elevator boot starts at lower flow rates when compared to the vertical and forward position. That explains the extreme error difference for the backward position at a target flow rate of 3.6 kg/s.

Conclusions

The new flow sensing technique presented encouraging performance for mass flow rate measurement in bucket conveyors. The following specific conclusions can be drawn from the data reported in this study.

- The sensor exhibited satisfactory response in the range of 0 to 3.4 kg/s with an elevator speed of approximately 120 rpm. Above this flow rate, the limited elevator capacity provoked a grain build up in the elevator boot and prevented the sensor from responding properly to the flow rate.
- The calibration slopes were fairly consistent throughout the calibration tests. Intercept drift observed during the tests indicated that periodic zero load offset compensation should be considered during data collection.

Table 7. Error in accumulated mass measurement of soybeans at different tilt angles.

	Accumulated Mass Measurement Error (%)		
Target Flow (kg/s)	Vertical	Forward (6°)	Backward (6°)
1.8	-4.5	7.6	2.5
2.7	-3.8	1.1	5.2
3.6	1.5	5.0	26.7
Average	-1.3	7.5	11.0

Table 8. Error in accumulated mass measurement of corn at different tilt angles.

	Accumulated Mass Measurement Error (%)		
Target Flow (kg/s)	Vertical	Forward (6°)	Backward (6°)
1.8	0.2	11.3	-1.5
2.7	-1.4	8.6	4.0
3.6	-0.3	8.1	36.8
Average	0.1	11.4	10.9

- A grain flow rate of 3.3 kg/s caused the highest standard deviation (0.07) in the instantaneous flow rate measurement. At a two SD level, the deviation at 3.3 kg/s was ±4.2% and the deviation at 1.6 kg/s was ±4%. The average accumulated mass errors were less than 3.1% and the maximum accumulated error was 4.9% at a flow rate of 1.8 kg/s.
- For the dynamic flow tests, problems with the reference data hampered quantitative performance analysis, but the sensor seemed to respond satisfactorily to the mass flow rate changes based on target flow rates.
- The 13-s steady state response time of the sensor would cause an along-track resolution of approximately 18 m considering a typical harvester operation speed of 5.0 km/h.
- The tilt of the elevator with respect to its vertical axis had an influence on the sensor performance. The worst situation was backwards tilt, which would be caused by the machine going uphill.

The cost, simplicity and ease of retrofitting the device on the machine make this sensor technology a suitable alternative mass flow sensor for a yield monitor system on a pull type dry edible bean harvester, and future research should be conducted to refine the calibration and test it in the field.

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