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MEASURING MASS-FLOW-RATE AND MOISTURE ON A LARGE SQUARE BALER

by

Kevin J. Shinners	**Professor of Agricultural Engineering**
Neil G. Barnett	**Former Graduate Research Assistant**
Walter M. Schlesser	**Graduate Research Assistant**

Department of Biological Systems Engineering
University of Wisconsin – Madison

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Summary: Starwheel encoder displacement as measured by a rotary encoder was well correlated with volumetric and mass-flow-rates. This systems output could adequately predict mass-flow-rate with correlation coefficients in the range of 88% - 96% in alfalfa and straw with relative prediction errors in the range of 8% - 10% in straw. Net average plunger force was not well correlated with volumetric or mass-flow-rate. Plunger force correlation coefficients were less than 60% on alfalfa and 40% in straw. Plunger force pulse width produced slightly better correlation coefficients, with values less than 70% on alfalfa and 40% in straw. The dynamic weight of the bale on the bale chute was reasonably well correlated (R^2 = 81%) with static bale weight. Dynamically weighing the bale on the bale chute would be valuable part of a mass-flow measurement system on a large square baler. Neither a capacitance nor NIR moisture sensor predicted bale moisture compared to oven dry bore samples. Concerns exist with both sensors relative to the inadequate volume of the sensing zone on the bale.

Keywords: Forage, Mass-flow-rate, precision farming, mower-conditioners

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Department of Biological Systems Engineering
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Introduction

During the last 10 years, there has been increasing interest in developing precision farming practices in all areas of agriculture. Most of the attention has been directed at grain markets. More recently, there have been developments in other areas, most notably cotton, potatoes, sugar beets, sugar cane, and vegetable crops. In terms of machinery research, much of the attention has been focused on measuring crop yield. This typically involves measuring mass-flow-rate, moisture content, and on some machines, the width of cut.

Very little effort has been made to monitor yield in forage crops as compared to grain, cotton, or potatoes. To date, all attention had been focused on two machines – the forage harvester and round baler. Different concepts have been attempted with the forage harvester (Mains et al., 1984; Vansichen and De Braedemaeker, 1993; Aurnhammer et al., 1995; van der Weft et al., 1994, Godwin and Wheeler 1997; Martel et al., 1998, Barnett and Shinners, 1998 and Oh Canada, 1999).

Two research groups have developed yield monitors for round balers (Wild et al., 1994; Wild and Auernhammer, 1997; Behme et al., 1997). These systems both involved load cells or strain gauges at the three support points of the machine (each axle and tongue). The mass increments measured by the systems were often very small compared to the mass of the baler itself (weight gain in 1 s was often less than 1% of tare weight). Dynamic forces from the tractor's engine and PTO, turning, and ground surface roughness all negatively affected the accuracy of the systems. Both groups recorded weight gain on-the-go, in addition to final bale mass, with the machine static after bale wrapping.

Static weight measurements were more accurate than dynamic weight measurements. Behme et al. (1997) reported 50% correlation between bale mass as predicted by the system when baling compared to actual bale mass as determined using a separate field scale. When comparing predicted versus actual weight of the harvested crop over an entire field (12 ha), relative prediction errors were 2.6 and 5.3% for first and second cuttings, respectively. However, a plot or "cell" of this size dilutes the error considerably. The low correlation coefficients of the prediction models indicate that this system was not adequate to accurately measure mass-flow on-the-go. Wild and Auernhammer (1997) reported relative error for static measurements of bale mass to be in the order of 1% with their system. Low pass filtering and spline smoothing was used to reduce dynamic effects so that relative errors of predicted bale weight ranged up to $\pm$ 10%. Systems that weigh the baler and its contents will be expensive relative to the cost of the baler.

Little work has been done to measure crop yield or mass-flow on rectangular balers. Chevako (1984) suggested a method for determining the weight of small square balers by measuring the reduction in flywheel speed and torque impulse in the system each time a bale was ejected with a bale ejector. Commercial systems has been developed to measure the weight of bales on the bale chute just before the bale drops onto the ground (Meadowbrook Scale, 1998; Case IH, 1999). These systems are designed for 3-tie, intermediate, and large square balers. Large square bales can weigh 1 tonne, and hay from a considerable area is used to form each bale. A system that weighs each bale after formation would require a large cell size which might be too large to determine local yield variations. Despite the fact that the number of large square balers sold each year is lower than small square and round balers, it is on these machines where the greatest potential for yield monitoring exists. These machines are relatively expensive, so owners are usually custom operators or large hay producers who would be interested in a feature like yield monitoring.

A commercial system based on electrical conductance between two electrodes can measure bale moisture (Harvest-Tec, 1997). Van Loo (1978) used a similar principle to measure moisture content of straw in a combine. He found correlation coefficients as high as 78% in some crops. Other possible principles for measuring the hay moisture content in balers is through dielectrics and near infra-red spectrosophy (NIR).

The objectives of this study were to design and fabricate systems to measure mass-flow-rate and moisture content on a large square baler; to test the developed systems in alfalfa hay and wheat straw; and to develop calibration equations for each system and evaluate the accuracy of the equations.

Sensor Systems

Machinery Description

A John Deere model 100* large square baler with a bale cross section of 80 x 80 cm was used (fig. 1). Maximum bale length was 2.5 m. Crop was compacted with a mechanically driven plunger, producing 50 strokes per minute with a stroke length of 75 cm. Bales had 4 rows of twine around the perimeter. Bale density was maintained by hydraulically positioned chamber rails, which were controlled by a self-contained electro-hydraulic system.

FIGURE 1 -- JOHN DEERE MODEL 100 BALER IN WHEAT STRAW

Measurement of Bale Displacement in the Chamber

Stuffer forks move crop from the pre-compression chamber into the main bale chamber, while the plunger is in the "home" or fullest forward position. The stuffer forks withdraw, and then the plunger packs the new charge of hay into the bale chamber, forcing some of the compressed and tied crop to be forced out of the chamber. The points of a star-shaped wheel (starwheel) engage the crop in the bale chamber. The starwheel shaft is connected to the baler knotter clutch such that when sufficient bale displacement has occurred the knotters are engaged.

It was hypothesized that a sensor that would measure the rate of rotation of the starwheel would provide an output that is well correlated to volumetric and mass-flow-rate of material. An additional starwheel was obtained and mounted on the top of the bale chamber. The starwheel shaft was supported by flange-mount ball bearings to allow for free rotation. To measure the rate of rotation of the wheel, an optical encoder was connected to the output shaft of the starwheel by a flexible coupler (fig. 2). The encoder had a resolution of 600 counts per revolution, or approximately 1.8 counts per degree.

* Mention of trade names does not imply endorsement by the University of Wisconsin.

FIGURE 2 -- STARWHEEL SENSOR SYSTEM

Plunger Force Measurement

Large square balers use strain gauge sensors to measure the load on each side of the mounting for the plunger gear box to insure even filling of the chamber so that bales are formed with tight, square edges. These sensors see a large force spike each time the plunger impacts the bale face. Since these sensors are a standard functional component of the baler, it would be attractive if the output could also be correlated with mass-flow-rate. Two hypotheses were developed for this sensor system: (1) the total integrated or average force from the plunger load sensors would be proportional to mass-flow-rate; and (2) the pulse width of the force impulses would be proportional to mass-flow-rate. Additional parameters that would affect the plunger force included plunger crank speed, bale chamber hydraulic pressure and crop moisture. The plunger sensors were part of the self-contained electro-hydraulic system on the baler. A signal conditioning unit was dedicated to the sensors that regulated excitation voltage at 10 VDC, and amplified the low level, differential voltage produced by each sensor to produced two single ended high level voltage signal, that was used by the main processor for control purposes. The signal wires between the amplifier and on-board processor were spliced to obtain the plunger force signals in the form of high level, single ended, analog voltages. Due to the difficulty involved with calibrating this system, all data are presented in terms of sensor output (volts) and not force (N).

Weight of Bale on Bale Chute

The weight of the bale, along with the bale formation time, can be used to determine mass-flow-rate. This system will only generate one data point per bale, so yield map cell size would be quite large. However, bale weight could be useful data in conjunction with other more instantaneous data such as the starwheel displacement. The weight of the finished bale as it resided on the bale chute was determined (1999 only) by placing load cells at the chute pivot points and in series with the chute support chains. The pin load cells had 27 kN capacity and the load cell in the support chain was 9 kN capacity. The chute position was dropped about 150 mm to enhance separation of the finished bale from the bale still in the chamber. A spring-loaded switch was placed at the front of the bale chute that provided the instrumentation system with a voltage spike when the finished bale fell from the chamber and closed the switch. The output of the three load cells was then collected for 5 s to estimate the weight of the bale.

Additional Sensors

A magnetic pickup was installed to measure the knotter drive gear speed and hence plunger crank speed because of a direct gear drive between the two components. Proximity stitches were installed next to one spring-loaded dog to measure bale slices, and next to the twine arm to indicate when bales were tied off, so data from bales made in succession could be separated for data analysis. A pressure transducer was also installed in a hydraulic line for the chamber rail positioning. The hydraulic pressure at this point should be directly related to the force from the crop on the rails.

Moisture Sensors

A prototype flat-plate capacitance moisture sensor was flush mounted to the left hand side of the bale chamber at about the center of the bale height. The sensor's output was a voltage related to the capacitance between the sensor plate and ground.

A Mesa "Moisturite" near-infrared spectroscopy (NIR) moisture sensor was placed at the top of the bale chamber near the knotters. This sensor

Instrumentation

For the large square baler mass-flow measuring system, the requirements for the individual sensors were determined (table 1). To perform the data acquisition, a portable computer with two PCMCIA slots was used. LabVIEW® (Version 4.1) software was used to collect and manipulate the data. The card performed all analog to digital conversions and pulse counts. All signals except that from the magnetic pickup were coupled into a connector block, and read directly by the PCMCIA DAQ card as analog inputs. The pulse counts coming from the starwheel sensor were wired into the two digital counters on the DAQ card. The signal from the knotter drive magnetic pickup was fed to a 5B45 frequency input module was used to convert speed pick-up frequency to a voltage which was then read by the DAQ card.

TABLE 1 -- SENSOR REQUIREMENTS

Sensor	Measurement Range	Sensor Excitation	Output Signal
Starwheel encoder	0-100 pulse/sec	12 V	Pulse
Plunger force (load pins)	0-10 V	On machine	0-10 V
Bale weight on chute		10 V	
Pressure transducer	0-1800 kPa	5 V	0-5 V
Slice proximity switch	40-60 pulse/min	12 V	Pulse
Twine arm proximity switch	0-.5 pulse /min	12 V	Pulse
Knotter drive magnetic pickup	0-200 rev/min	None	Pulse

Most of the data from the baler experiments baler were sampled at a rate of 120 Hz with every 24 points averaged (netting 5 data points per s) and written to an ASCII spreadsheet file. It was important to sample all channels as fast as possible so as to produce the most accurate profile of the plunger force spikes, which occurred at a frequency of 0.83 Hz. Sampling at 120 Hz, and averaging 24 points at a time was the fastest combination the system would allow, as counting pulses from the encoder diminished system performance. For this reason, 6 additional data runs were done in wheat straw at a sampling speed of 150 Hz, averaging only every 2 points, thus writing 75 data points per s, per sensor to the file. For these data runs, no data was recorded from the starwheel sensor. This attempt at faster sampling rates was done to see if a more accurate profile of the plunger force pulse would improve correlation to mass-flow-rate. No filtering was used when acquiring data.

Experimental Conditions and Tests Conducted

The sensors systems were evaluated at the University of Wisconsin's Arlington Agricultural Research Farm during the summer of 1998. The bale chute weighing system was evaluated in 1999. In 1998, four days of tests were conducted harvesting alfalfa and straw (wheat). Dry matter yields ranged from 4-6 and 3-5 tonnes/ha, for alfalfa and straw, respectively. Approximately 25-40 bales were made each day.

To vary machine throughput, four different ground speeds were evaluated each day when harvesting straw (4.7, 6.5, 8.1, 10 km/hr). At least two test runs consisting of 3-9 bales each were conducted at each ground speed. Straw bales were harvested over 3 days. On the last 2 days, 3 additional data runs were taken (3 ground speeds, 4 bales per test run) at the faster sampling rate discussed earlier. Bales were tagged according to data run and order they were formed. Far less alfalfa was available for harvesting, so data was taken at three ground speeds (4.7, 8.1, 13 km/hr) on a single test day. Three test runs were done at each speed, with 1-4 bales produced during each test run. Compression rail pressure was kept as constant as possible using the output of the bale monitor and dial gauge on the front of the machine.

In 1999, a single day of testing was done to evaluate the bale chute weighing system. Third cutting alfalfa was used and the baler was operated at 4.7, 8.1, 13 km/hr to vary throughput. Three replicate tests were done at each speed, with three bales produced during each test.

The data acquisition system was started before baling began, and was stopped after baling ended. The length of the windrow determined the length of the data run, which was typically 2 to 5 min. Bales were collected, transported to the farmstead, and weighed on a certified platform scale (312 kN capacity, 90 N resolution). Bale mass was divided by the time required to form the bale to obtain mass-flow-rate. Bales were measured for length (referenced from the center of each end, 12 mm resolution) using a measuring tape. To obtain volumetric flow-rate, length was multiplied by cross-sectional area, then divided by time required to form the bale. In addition, bales were bored once each for moisture content. Samples were cut with a hydraulically operated boring machine in the end of each bale, cutting a bore 50 mm in diameter approximately 400 mm into the bale. Wet basis moisture was determined by drying at 103 ^{o}C for 24 hours as per ASAE standard S328.1. This allowed for a calculation of dry matter harvested in each run.

TABLE 2 -- SUMMARY OF TESTS

Crop	Straw	Alfalfa	Alfalfa*
Number of bales	112	26	27
Average bale length, m	2.24	2.14	
Average bale mass, wet kg	181	232	
Average bale density, wet kg/m^3	126	232	
Average bale moisture, % w.b.	5.1	20.6	
Average slices per bale	38	53	

* - Tests conducted in 1999

Data Analysis

Each data run began with a partially formed bale in the chamber. This allowed the machine to reach steady-state before bales were formed that were used in the data analysis. Post processing of the data had to be done to remove the partial bales at the beginning and end of each run, and to split up data into individual bales, using the output of the proximity switch on the twine arm. Individual bales were separated at each voltage drop produced by the proximity switch detecting twine arm movement. Data from each bale were moved to a new spreadsheet for subsequent analysis.

Data from all sensors were averaged to obtain a "bale average value", for use in subsequent analysis. For each bale, a cumulative pulse count was recorded from the starwheel encoder. The final cumulative pulse count was subtracted from the initial value, then divided by time of bale formation to obtain average pulse count per second per bale. This value, along with average plunger crank speed, and moisture content were regressed as independent variables against volumetric flow-rate, wet mass-flow-rate, and dry mass-flow-rate, respectively. When hay moved through the bale chamber, the starwheel was displaced in one direction by the compressing hay and slightly in the opposite direction by the decompressing hay after the plunger retracted from the bale face. Due to the fact that the opposite rotation could not be eliminated automatically by the sensor, it was accounted for in the data manipulation. A dynamic plot illustrating counter output for bales formed at three different ground speeds (or mass-flows) is presented in fig. A. The output at 0 km/hr represents the cumulative pulse counts caused by rotation of the starwheel from decompression and recompression of the crop in the chamber from plunger impact on the bale face.

Bale length, mass, and moisture content were tabulated and added to the data set. From this information and the time required to form the bale; volumetric-flow-rate, average wet mass-flow-rate, and average dry mass-flow-rate were calculated for each bale. These values were used separately as the dependent variables in a multiple regression analysis. An analysis was performed for each variable with average starwheel counts per second, average plunger crank speed, and bale moisture content as independent variables. Regression equations were developed for straw and for alfalfa. Only variables with $p < 0.05$ were kept as parameters in the predictive models.

As was previously stated, two hypotheses were made for the plunger force sensors, one was that mass-flow would be correlated to the integrated force pulses from the sensor and/or that the other was that the width of the force pulses would be correlated to mass-flow-rate. The data handling procedures for evaluating these two hypotheses were very different.

To evaluate the first hypothesis (integrated force pulse), it was first assumed that averaging the data from a bale would provide the desired values (averaging would be the same as integrating the curve and dividing by time and then dividing by sampling rate). When the data were further examined, it was realized that the baseline of the two sensors (the part of the sensor output while the plunger was not in contact with the bale face) tended to float somewhat during operation. Possible causes of the floating signal were changing stresses on the bale chamber or electrical system noise. To try and account for the floating baseline within and among bales, the tenth percentile was calculated for each force data set and was subtracted from the average, to provide a value, hereafter referred to as net-average-plunger-sensor-output (NAPSO). Different percentiles were tried in the analysis, however, it was found that the tenth percentile gave the best indication of sensor baseline value. A percentile function worked well for this task because it was not weighted by all of the data, as would a mean value. Figure B illustrates the output from one sensor along with the tenth percentile (baseline) and the net-average-plunger-sensor-output. Values for net-average plunger-sensor-output were tabulated, for each bale and were used in regression analysis similar to that described for the starwheel sensor data.

$$\mathrm{NAPSO} = \frac{\mathrm{mean}\,(a_1 \ldots a_n) - 10^{\mathrm{th}}\ \mathrm{percentile}\,(a_1 \ldots a_n)}{\mathrm{Time}}$$

A method was required to measure the width of each force pulse. A threshold value was set above all baseline data and the “count” function in a spreadsheet package was used to sum all points above this threshold. The pulse width was then the unitless total number of data points above the threshold value divided by the total number of data points in the sample. This pulse width the value was then used in subsequent regression analysis in a similar fashion to the procedure described for the starwheel sensor data.

$$\mathrm{PW} = \frac{\text{Data Points Above Threshold}}{\text{Total Number of Data Points}}$$

It was desired to use a percentile to determine the pulse width threshold because this statistic was not weighted by the entire sample. The threshold had to be high enough to exclude the baseline data, but low enough to capture the full width of the force pulse. In order to be above all baseline data, a percentile threshold of more than 50 was required, and this led to low correlation coefficients in the regression models. A new threshold was chosen which added a constant to the 25th percentile. To accommodate the floating baseline, a moving threshold was calculated which used the 25th percentile of the previous 5 s data plus a constant. The constants added to the 25th percentile were selected by trial and error to obtain the best correlation in the regression models. The values were different for the right and left sensors, and the two sampling speeds. A constant for a given sensor location or sampling speed was the same for alfalfa and straw. Figure C illustrates dynamic force data acquired from both plunger force sensors recorded at 5 Hz, and the moving thresholds for each sensor.

Two data sets were analyzed for pulse width. Three additional data runs were acquired on two different days when harvesting wheat straw. These data were sampled at 150 Hz and written to a file at 75 Hz (every 2 points averaged). Each data set was analyzed independently to determine if a faster acquisition rate would be necessary to accurately measure pulse width. Figure D illustrates a dynamic plot of data acquired at 75 Hz, and the moving threshold that was used for this data.

The whole data set acquired at the slower acquisition rate with wheat straw was split before data analysis. Half of the data were used to calculate the calibration equation for the sensor, while the other half of the data were kept to calculate the relative error of prediction for the equation generated. Relative error of predicted was calculated via the following formula:

$$\text{Relative Error} = \frac{|\text{Predicted Value} - \text{Actual Value}|}{\text{Actual Value}} \times 100$$

The relative error statistic has been used to provide an indication of accuracy for mass-flow sensors used for harvesting other crops such as grain, potatoes and sugarbeets. Prediction errors are usually provided on a "whole load basis" which tends to dilute error. A sufficient amount of data was not collected in alfalfa to generate a statistic of relative error for the systems evaluated.

Results

Equations were generated to predict volumetric flow-rate, wet mass-flow-rate, and dry mass-flow-rate. Mass-flow-rate and volumetric flow-rate were generally well correlated (fig 6.9). Summary statistics for the crop harvested are presented in table 2.

Starwheel Encoder Sensor

The starwheel encoder's output in both alfalfa and wheat straw was well correlated with mass and volumetric flow-rates (fig. 6.10,6.11). Multi-parameter regression analysis was performed for the starwheel sensor data versus volumetric and mass-flow-rates. The following models were developed for the starwheel sensor along with correlation coefficients (R^2), standard error of calibration (SEC), and number of observations (N) (table 6.3).

TABLE 3 -- REGRESSION MODELS USING STARWHEEL SENSOR OUTPUT - ALFALFA

VFR = 0.11 + (9.60E-3*SWEC) – (2.62E-3*PCS)		
R^2	**SEC**	**N**
96%	0.43	26

WMFR = 30.36 + (0.21*SWEC) – (0.70*PCS)		
R^2	**SEC**	**N**
94%	0.73	26

DMFR = (0.19*SWEC) – (0.13*PCS)		
R^2	**SEC**	**N**
94%	0.59	26

High correlation coefficients and low standard error of calibration values characterized all alfalfa calibration curves (figs 6.12,6.13). Results in wheat straw produced slightly lower correlation coefficients, but similar standard error of calibration values (fig. 6.14, 6.15). Plots generated for wheat straw were created with data independent of calibration data, therefore there were slight differences in R^2 values between the models, and the trendlines presented on the plots. Average relative errors were 8.4, 10.8, and 10.7% for predictions of volumetric, wet-mass, and dry mass-flow-rates in wheat straw, respectively.

TABLE 4 -- REGRESSION MODELS USING STARWHEEL SENSOR OUTPUT - STRAW

VFR = (1.09E-3*SWEC) – (0.70E-3*PCS)		
R^2	**SEC**	**N**
90%	0.61	57

WMFR = 12.53 + 0.12*SWEC – 0.31*PCS		
R^2	**SEC**	**N**
90%	0.53	57

DMFR = 12.45 + 0.11*SWEC – 0.30*PCS		
R^2	**SEC**	**N**
98%	0.51	57

Net Average Plunger Force

Multiple regression analysis of data using net average plunger sensor output as the main independent variable did not yield high correlation coefficients. The results from data taken in wheat straw were particularly poor. Sensor output alone illustrates the difference in the correlation coefficients between alfalfa and wheat straw (fig. 6.16, 6.17).

Similar to the starwheel encoder sensor, multiparameter models were developed to use net average plunger sensor output as a predictor of mass-flow-rate. Models were developed when harvesting straw, however net average plunger sensor output was not significant at the $p < 0.05$ level, so models are not presented here (table 6.4).

Table 6.4 -- Multi-parameter regression models using net average plunger sensor output as a predictor of mass and volumetric flow rates

	R^2	SEC	N
Alfalfa - Volumetric flow-rate (fig. 6.18)			
[7] VFR = 0.36 + (0.45*NAPSO) – (7.17E-3*PCS)	73%	1.08	26
Alfalfa - Wet mass-flow-rate (fig 6.19)			
[8] WMFR = 74.33 + (116* NAPSO) – (1.52*PCS)	77%	1.48	26
Alfalfa - Dry mass-flow-rate (fig. D.53)			
[9] DMFR = 56.89 + (90.67* NAPSO) – (1.16*PCS)	75%	1.20	26

The addition of plunger crank speed to the model improved the correlation significantly over a single parameter correlation (fig. 6.18, 6.19). This is most likely due to the integral relationship between the force on the bale case and plunger crank velocity. Slower speeds will result in larger charges in the bale chamber, hence larger force spikes.

Plunger Force Pulse Width

Correlation between the calculated plunger force pulse width and volumetric or mass-flow-rates were reasonable in alfalfa, but poor in wheat straw for all of the data sampled at 120 Hz and stored at 5 Hz (table 6.5, figs. 6.20, 6.21). The addition of plunger crank speed to the model increased correlations marginally in alfalfa and significantly in wheat straw (table 6.6). As was the case with other regressions models calculated, moisture content was not a significant factor in the model.

The predicted versus actual volumetric and mass-flow-rates are plotted for alfalfa (using calibration data) on figures 6.22 and 6.23, and for wheat straw (using verification data) figures 6.24 and 6.25. Correlation coefficients listed on plots 6.24 and 6.25 might not necessarily agree with those listed on the figures because half of the wheat-straw data were used to construct the calibration equation, while the remaining data was used to calculate the error of prediction. Relative error values in wheat straw were calculated at 16.7, 23.4 and 15.0% for predictions of volumetric, wet-mass, and dry mass-flow-rates, respectively. Insufficient data were available to verify (i.e. generate relative error of prediction) the calibrations in alfalfa.

Table 6.5 -- Multi-parameter regression models using plunger force pulse width as a predictor of mass and volumetric flow rates (Slow sampling speed)

	R^2	SEC	N
Alfalfa – Volumetric flow-rate (fig 6.22)			
[10] VFR = (0.30*PW) – (1.15E-3*PCS)	75%	1.02	26
Alfalfa - Wet mass-flow-rate (fig. 6.23)			
[11] WMFR = (69.16* PW) – (0.27*PCS)	77%	1.42	26
Alfalfa - Dry mass-flow-rate (fig. D.58)			
[12] DMFR = (53.73* PW) – (0.21*PCS)	76%	1.15	26
Wheat Straw - Volumetric flow-rate (fig. 6.24)			
[13] VFR = 0.32 + (0.21*PW) – (6.66E-3*PCS)	66%	1.28	51
Wheat Straw - Wet mass-flow-rate (fig. 6.25)			
[14] WMFR = 38.06 + (26.63* PW) – (0.78*PCS)	60%	1.14	51
Wheat Straw - Dry mass-flow-rate (fig. D.60)			
[15] DMFR = 36.76 + (25.20* PW) – (0.77*PCS)	60%	1.08	51

The small data set acquired at fast sampling speed (sampled at 150 Hz, stored at 75 Hz) yielded a higher correlation between pulse width and volumetric or mass-flow-rates (table 6.6, fig 6.26). The actual pulse width values were lower for data acquired at high sampling speed. This is due to the fact that the threshold set for data acquired at a faster rate had to be set higher to avoid the baseline noise in the plunger force signal.

Table 6.6 -- Multi-parameter regression models using plunger force pulse width as a predictor of mass and volumetric flow rates (fast sampling speed)

	R^2	SEC	N
Wheat Straw – Volumetric flow-rate (fig. 6.27)			
[16] VFR = (0.58*PW) – (1.34E-3*PCS)			
	62%	1.39	21
Wheat Straw - Wet mass-flow-rate (fig. 6.28)			
[17] WMFR = 74.52*PW – 0.18*PCS			
	63%	1.12	21
Wheat Straw - Dry mass-flow-rate (fig. D.63)			
[18] DMFR = 70.75*PW – 0.17*PCS			
	62%	1.08	21

The main factor, pulse width was better correlated with the dependent variables for data taken a faster sampling rate (fig. 6.26), however the difference is not significant for the multi-parameter model. Very large deviations between the predicted and actual values were present at high feedrates (fig. 6.27, 6.28). Some of these points could have been outliers, however insufficient amounts of data were taken at faster sampling rates to be able to determine this. The data set used to calculate the calibration equation at a faster data acquisition rate was based on only 21 data points, while the equations generated for data acquired data slower rate was based on 51 data points.

Discussion

Moisture was not a significant factor in any model. This is most likely due to the fact that the range of moisture values covered for either set of data was not wide enough to evaluate its true effect. Wheat straw is generally harvested at low moistures, so its effect on a prediction of flow-rate would be minimal.

Prediction equations generated for all sensors in straw generally had lower correlation coefficients and higher standard error of calibration values than was found in alfalfa hay, despite the fact that more than double the data points were used in the calibration. While harvesting alfalfa hay, the bale case pressure was observed (analog pressure gauge on the front of the baler) to remain relatively constant at about 360 kPa, however when harvesting wheat straw the bale case pressure varied from 200 kPa to 900 kPa for one density setting. The variable packing pressure is thought to be a major reason the systems that used the plunger force sensors did not perform well in wheat straw. A lower case pressure would require less force to push the column of hay through the bale chamber. It appears that the effect of case pressure is important and should be accounted for.

In addition to bale case pressure, the compaction characteristics of straw versus alfalfa hay may be responsible for the lower correlation values. Straw is more difficult to compact than alfalfa, and springs back more when the plunger retracts from the bale face, resulting in less uniform compaction than was found in alfalfa hay. These compaction characteristics would have an effect on all sensors, most importantly the plunger force sensors. The lower correlation between volumetric flow-rate and mass-flow-rate for straw than alfalfa hay further illustrates the different compaction characteristics of wheat straw (fig. 6.9).

Predicted values for volumetric and mass-flow-rates tended to have lower accuracy at low throughputs, particularly with the starwheel encoder sensor. It was observed that at low throughputs (ground speeds), small charges were fed into the main bale chamber by the feeder forks. These small charges tended to stay on the bottom of the bale, resulting in a higher density of material on the bottom of the bale. In extreme cases (very low feedrates) trapezoid shaped bales were formed. Because the starwheel encoder was located on the top of the bale chamber, these non-uniform charges may not have engaged the starwheel properly. Mounting the starwheel encoder system on the bottom or side of the bale chamber may decrease errors at low feedrates. However, these low feedrates may not be representative of actual practice.

Of the systems evaluated, the starwheel encoder system provided the best results. With high correlation coefficients for alfalfa, significant improvement would be difficult. The correlations were best with volumetric flow-rate, which was logical due to the fact that a displacement measurement was being made.

Of the two methods evaluated using the data from the plunger force sensors as their basis, the measurement of pulse width appears to be the most promising. The correlation between the pulse width and volumetric or mass-flow-rates was much better than correlations found with net average plunger sensor output. These differences are not as evident in the multiparameter models developed, as the inclusion of plunger crank speed improved correlations greatly with net average plunger sensor output. Pulse width measurement is believed to be less effected by the maximum force seen by the sensors, and would therefore be less effected by crop compaction characteristics, as straw requires more force to compact than does alfalfa hay.

Recording data at faster acquisition rates appears to provide a value for pulse width that alone is more accurately correlated to mass-flow-rate, but when evaluating multiparameter models the effect of sampling at a faster rate was not as significant. However the analysis of the data taken at faster sampling rate was based on approximately 40% as many points as the data acquired at the slower acquisition rate. It is possible that larger data set for data acquired at a faster speed would yield higher correlation values.

There is the possibility that the results from analysis of plunger force data (net average plunger sensor output and plunger force pulse width) could be improved significantly. Problems with the sensors resulted in difficulties in zeroing and scaling the outputs. It appeared that problems existed with the sensors, particularly the right sensor, where output was always at a much lower level than the left (fig. 6.7). A new sensor bar could yield improved results. The data collected from the sensors in 1998 appears to illustrate some potential for these methods. Incorporating bale chamber pressure transducer may bring about significant improvement in the models. It is possible that other methods to calculate pulse width could yield more accurate correlations, and should be explored.

6.9 Summary of Results

Parameters used to predict volumetric and mass-flow-rates of wheat straw and alfalfa hay harvested with an intermediate square baler were: (1) rotation of a starwheel engaging the bale as measured by an optical encoder; (2) net average plunger force; and (3) plunger force pulse width.

Mass-flow-rate in the baler was measured by weighing the bale, then dividing the mass by the amount of time that was required to form it. Volumetric flow-rate was found by measuring the bale length and cross section and similarly dividing it by formation time.

Starwheel encoder system output was well correlated with volumetric and mass-flow-rates. This system's output could adequately predict mass-flow-rate with correlation coefficients in the range of 88-96 % in all crops and relative prediction errors in the range of 8-10% in wheat straw.

Net average plunger force was not well correlated with volumetric or mass-flow-rates. Plunger force correlation coefficients were less than 60% in alfalfa and 40% in wheat straw. Multiparameter regression models slightly improved the correlation in alfalfa.

Plunger force pulse width produced slightly improved correlation coefficients, with values less than 70% in alfalfa and 40% in wheat straw. Multiparameter regression models produced R^2 values slightly above 70% in alfalfa and slightly above 60% in wheat straw.

Sampling at higher sampling rates may improve correlation of pulse width with mass-flow and volumetric flow-rates. Correlation of pulse width with mass-flow-rate volumetric flow-rate alone yields higher correlation coefficients for data acquired at 75 Hz as opposed to data acquired at 5 Hz. Results are inconclusive for multiparameter models.

All data acquired from plunger force sensors may be improved by changing the force sensor bar and including the effects of bale case pressure.

6.10 Nomenclature

VFR = Volumetric flow-rate, m^3/s
WMFR = Wet mass-flow-rate, kg/s
DMFR = Dry mass-flow-rate, kg/s
SWEC = Star wheel encoder count
NAPSO = Net average plunger sensor value (volts)
PW = pulse width – fraction exceeding threshold
PCS = Plunger crank speed, strokes/min

6.11 References

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