Sensors to measure mass-flow-rate through a forage harvester

H. MARTEL¹ and P. SAVOIE²


Martel, H. and Savoie, P. 2000. Sensors to measure mass-flow-rate through a forage harvester. Can. Agric. Eng. 42:123-129. Four different sensors were used to estimate mass-flow-rate and moisture on a pull-type forage harvester. The sensors measured feedroll displacement, crop impact force against a hinged plate located above the blower, the frequency drop of a capacitance controlled oscillator near the end of the spout, and the number of light beam interruptions by forage particles in the spout. Tests were conducted in a corn field with a commercial forage harvester modified with the first two sensors (feedroll displacement, impact force), and in the laboratory using a forage blower adapted to a forage harvester spout for the last two sensors (capacitance controlled oscillator, light beam interruption). The capacitance controlled oscillator was also characterized in a static mode in the laboratory with alfalfa and timothy particles. When testing in a corn field, good correlations were obtained between estimated mass-flow-rate and either the feedroll displacement (R² = 94%) or the crop impact force (R² = 95%). When testing in the laboratory, the correlation between mass-flow-rate and the oscillator drop was very good (R² = 96%) after a correction procedure. The number of light beam interruptions was not well correlated with mass flow (R² = 43% for LEDs placed after the capacitor and R² = 6% for LEDs placed before the capacitor). During static measures with alfalfa and timothy, the oscillator frequency drop was also related to crop moisture but calibration corrections were required to consider differences between crop species and chop lengths.

INTRODUCTION

Precision agriculture may be applied to forage crops to measure local yield variations in the field, to estimate total crop yield harvested, and to plan the feeding program on a livestock farm. Forages present a particular challenge compared to most other crops because their moisture content can vary at the time of harvest from as low as 10% for hay to up to 80% for silage. Therefore, moisture and mass of forage crops must be measured simultaneously and for a relatively wide range of moisture contents.

If mass and moisture are to be measured at the time forage is removed from the field (usually during a wilting period), appropriate sensors are likely to be different for hay and silage crops. Hay is typically baled and stored at moisture contents between 10 and 20% while crops for silage are typically harvested and stored at moisture contents between 40 and 70%. Chopped forages present an additional constraint because they are not accumulated in the harvester as opposed to baled forages which are accumulated until a bale is formed and allow weighing within the baler.

Estimation of material flow in a forage harvester will therefore have to rely on indirect measurements that are correlated with mass and moisture. Several studies have examined a number of sensors in forage harvesters such as a feedroll displacement transducer (Mains et al. 1983; Barnett and Shinners 1998), an infrared emitter-receptor system (Bull 1993), a radioactive isotope emitter-receptor system (Auernhammer et al. 1995), impact force measurement, or a combination of other sensors (Barnett and Shinners 1998). Marcotte et al. (1999) provided a critical review of various sensors which have been considered in forage harvesters. Signals measured by such sensors may be more or less influenced by total mass flow and moisture flow.

The objective of this research was to assess a selected number of sensors installed within a forage harvester and the relationship between the observed signals and mass and moisture flow variations.
a volume sensor composed of light emitting diodes (LEDs) on one vertical side of the spout and photo transistors on the other side. The position of these four sensors within the forage harvester is illustrated in Fig. 1.

The load cell was an "S" type with a capacity of 216 N. It measured the impact force caused by the moving forage particles against the hinged plate with a surface area equivalent to the chute width (235 mm) by a length of 500 mm. The displacement transducer was a water-resistant LT model sensor (Cymatix, Burlingame, CA) with a 0-150 mm displacement measuring range. These two sensors were fitted to the forage harvester for the field experiment. A portable computer with a data acquisition card (PCMCIA DAQ-700, National Instruments, Austin, TX) was used to collect signals at a frequency of 37 Hz. This was the maximum frequency at which all sensors could be scanned individually and sequentially without interference.

The capacitance controlled oscillator was fabricated in-house with a model TS555CN timer operating in the astable mode at about 880 kHz (SGS Thomson Microelectronics, Marlow, England). This frequency was near the maximum operating frequency (≈1 MHz) of the timer and was chosen to minimize the displacement of free charges naturally present in the forage during a measurement period. The electronic circuit of the oscillator is shown in Fig. 2. Similarly the LED emitter-receptor was built in-house with 16 LEDs (880 nm, model KIE 7304, Knight Lites) placed vertically on one side of the spout and 16 photo transistors (model KID 7404, Knight Lites) on the other side of the spout. The 16 parallel light beams could be interrupted as forage particles flowed in the spout. The LED beam receptors (photo transistors) were scanned at a frequency of 37 Hz. As more particles flowed in the chute, more beams were expected to be interrupted and the signal attenuated to the receptors. The electronic design of the LED emitter-receptor is shown in Fig. 3. The capacitance controlled oscillator and the LED emitter-receptor were evaluated in the laboratory only.

**MATERIALS and METHODS**

**Instrumented forage harvester**

Sensors were placed either on a commercial forage harvester for field experiments or on the forage harvester's spout adapted to a blower for laboratory experiments. A pull-type forage harvester (Dion model 1224, 12 knives) was used for the field experiment. This harvester is designed to cut and blow forage unidirectionally without side displacement between the cutting cylinder and the blower. In the case of laboratory experiments, pre-chopped forage was fed from a horizontal belt conveyor to a Dion model 1660 flywheel type blower above which the spout of a 1224 forage harvester was fitted. The technical characteristics of the forage harvester and the blower are described in more detail elsewhere (Dion 1999).

Four types of sensors were selected: a load cell measuring the impact force against a hinged plate in the spout, a displacement transducer placed at one end of the two upper feedrolls to measure the vertical movement of the rolls' centerline, a capacitance controlled oscillator placed at the end of the spout to measure changes induced by the forage particles, and a volume sensor composed of light emitting diodes (LEDs) on one vertical side of the spout and photo transistors on the other side. The position of these four sensors within the forage harvester is illustrated in Fig. 1.

The load cell was an "S" type with a capacity of 216 N. It measured the impact force caused by the moving forage particles against the hinged plate with a surface area equivalent to the chute width (235 mm) by a length of 500 mm. The displacement transducer was a water-resistant LT model sensor (Cymatix, Burlingame, CA) with a 0-150 mm displacement measuring range. These two sensors were fitted to the forage harvester for the field experiment. A portable computer with a data acquisition card (PCMCIA DAQ-700, National Instruments, Austin, TX) was used to collect signals at a frequency of 37 Hz. This was the maximum frequency at which all sensors could be scanned individually and sequentially without interference.

The capacitance controlled oscillator was fabricated in-house with a model TS555CN timer operating in the astable mode at about 880 kHz (SGS Thomson Microelectronics, Marlow, England). This frequency was near the maximum operating frequency (≈1 MHz) of the timer and was chosen to minimize the displacement of free charges naturally present in the forage during a measurement period. The electronic circuit of the oscillator is shown in Fig. 2. Similarly the LED emitter-receptor was built in-house with 16 LEDs (880 nm, model KIE 7304, Knight Lites) placed vertically on one side of the spout and 16 photo transistors (model KID 7404, Knight Lites) on the other side of the spout. The 16 parallel light beams could be interrupted as forage particles flowed in the spout. The LED beam receptors (photo transistors) were scanned at a frequency of 37 Hz. As more particles flowed in the chute, more beams were expected to be interrupted and the signal attenuated to the receptors. The electronic design of the LED emitter-receptor is shown in Fig. 3. The capacitance controlled oscillator and the LED emitter-receptor were evaluated in the laboratory only.

**Field experiment**

Field measurements were carried out by harvesting whole-plant corn silage during the week of September 28, 1997 in Lennoxville, QC. A section of the field was separated into 24 plots measuring 1.5 m wide (the width of two corn rows) by 26 m in length. Six trials were carried out using two pairs of slow and high speed as illustrated in Fig. 4. The transmission was shifted rapidly to high or low gear to create a rapid change (± 10 to 20%) in mass-flow-rate (actual forward speeds were 4.7 and 5.8 km/h at low speed, and 6.1 and 8.3 km/h at high speed). The rapid change in forward speed was done to evaluate the sensitivity of sensors to a rapid change in the mass-flow-rate.

Yield samples were taken in each of the 24 plots by cutting a 1-m length over two rows at a random location along each of the 26 m long plot prior to harvesting. An average yield was estimated by grouping three plots in each section (trials 1, 2, and 3 grouped; trials 4, 5, and 6 grouped). The mass-flow-rate (wet...
matter per unit time) for each of the 24 sections was then estimated as:

\[ Q_{\text{exp}} = \frac{wVY_{\text{ave}}}{36} \]  

(1)

where:

- \( Q_{\text{exp}} \) = experimental mass-flow-rate (kg/s),
- \( w \) = corn harvester width (m),
- \( V \) = forward tractor speed (km/h), and
- \( Y_{\text{ave}} \) = yield, on a wet matter basis, averaged over three grouped plots (kg/m²).

The sensor outputs were averaged over each 26 m length after filtering as described below. The average sensor outputs were then correlated with the experimental mass-flow-rate for each section in each trial. Moisture content was estimated from four samples collected after forage harvesting four consecutive 26-m long sections in a single trial. Samples were oven dried at 103°C for 24 h to estimate dry matter and moisture content according to ASAE Standard S358.2 (ASAE 1999a).

**Signal filtering for the field experiment**

Data collected in the field were processed either with a low-pass filter or with one of two band-pass filters (Doebelin 1975). In the case of the low-pass filter, the cutoff frequency was 1 Hz for the load cell measuring the impact force in the spout and 3 Hz for the position transducer measuring feedroll displacement. The two band-pass filters isolated the signal within a frequency range of 0.5 Hz, in one case around the natural frequency (i.e. the occurrence of maximum amplitude) and in the other case between 14.0 and 14.5 Hz. The natural frequency varied from 3 to 10 Hz, depending on the sensor and the trial. The choice of the range for the second band-pass filter (14.0 to 14.5 Hz) was based on a frequency analysis.

The data retained for analysis in each plot started 3 s after each section change. This delay allowed for completion of the tractor gear and speed change after a manual sign given to the operator and acceleration or deceleration of the tractor.

**Dynamic laboratory experiment**

The dynamic laboratory experiment was carried out during the week of March 9, 1998. Whole-plant corn was previously harvested and chopped at 13 mm theoretical length at the Deschambault Experimental Farm (Deschambault, QC) and frozen immediately (October, 1997). The material was thawed a few hours prior to experimentation. Three feeding rates of 3.6, 7.2, and 10.7 kg/s were repeated three times and the nine tests were repeated on three different days (blocks). A measured quantity of chopped forage was placed on a horizontal, 6.4 m long conveyor that moved at 1.3 m/s.

The forage was fed into the blower and conveyed pneumatically through the spout past the sensors. The LED emitter-receptor system was placed after the capacitor during two blocks (6 replications) and before the capacitor during the other block (3 replications). The LED signals were analyzed on the basis of the number of light beams interrupted by forage particles at every scanning (37 Hz). The oscillator was calibrated with the blower running at zero particle flow. The variation in oscillation frequency was compared to variations in the wet mass flow. Due to hardware problems, data from the capacitance controlled oscillator were recorded only on the second day.

**Static laboratory experiment**

The static laboratory experiment was carried out with fresh alfalfa and timothy after a wilting...
The static laboratory experiment was a four-factor split-split block design. Two factors (crop species and quantity of dry matter in the capacitor) were completely randomized while maturity was the first split factor and moisture content was the second split factor. There were two replications for each treatment combination.

RESULTS and DISCUSSION

Field experiment

Wet matter yield of corn ranged from 6.7 to 10.6 kg/m² and averaged 8.6 kg/m². Average moisture content was 79% and dry matter yield 18.3 t/ha. Speed varied from 4.5 to 9.5 km/h while mass-flow-rate ranged from 15.2 to 32.2 kg/s. The low-pass filter provided a considerably better relationship (R² = 94.8%) than the two band-pass filters (R² = 8.4%, based on the natural frequency; R² = 1.4%, based on the frequency range of 14.0 to 14.5 Hz). The average low-pass filtered signals of the load cell in the spout per test run versus estimated mass-flow-rate are illustrated in Fig. 5. The linear relationship (R² = 94.8%) was:

\[ Q_1 = -0.611 + 2.46F \]  

(2)

where:

- \( Q_1 \) = predicted mass-flow-rate (kg/s) as a function of impact force, and
- \( F \) = impact force (N) measured in the spout.

The feedroll displacement transducer signals were also processed with a low-pass filter. The average feedroll displacement per test run versus estimated mass-flow-rate is shown in Fig. 6. The coefficient of determination \( R^2 \) was 93.7% and the linear relationship:

\[ Q_2 = -0.359 + 1.37D \]  

(3)

where:

- \( Q_2 \) = predicted mass-flow-rate (kg/s) as a function of feedroll displacement, and
- \( D \) = feedroll displacement (mm).

The low-pass filters provided a good relationship between mass-flow-rate and either the load cell in the spout or the displacement transducer at the feedroll. These observations are limited for a mass-flow-rate of 15 to 32 kg/s, where the average moisture of corn was 79%. This mass-flow-rate range corresponds to a harvest rate of 54 to 115 t/ha which is approximately between half and full capacity of the Dion 1224 harvester. The relationship between feedroll displacement or force against a plate in the spout might change for mass-flow-rates outside this range and for a forage harvester with a geometry different from the one used in this experiment.

Dynamic laboratory experiment

Chopped corn was fed in the laboratory through the blower-spout system at three mass-flow-rates of 3.6, 7.2, and 10.7 kg/s. The average moisture content of this frozen-thawed corn was 60%. The LED emitter-receptor system was placed either before or after the capacitor in the spout. Figure 7 shows a typical histogram of the number of beams interrupted by particles during two trials. Each trial lasted on average 4.9 s with a scanning frequency of 37 Hz. As the amount of forage used in a trial increased, one would expect the number of interrupted beams...
Fig. 7. Examples of signals from the LED emitter-receptor placed:
(a) after the capacitor; (b) before the capacitor.

beams to increase, causing the normal curve associated to the histogram to shift upward or to the right, or both.

Although the mass-flow-rate ranged from 3.6 to 10.7 kg/s, the average number of beam interruptions ranged only from 9.05 to 10.70 (out of 16 light beams). There was a slight tendency for the average median value to increase with mass-flow-rate (9.33, 10.02, and 10.09 for low, medium, and high mass-flow-rate, respectively). The linear relationship with \( R^2 = 43\% \) was:

\[
Q_3 = -36.1 + 4.40L
\]

where:
- \( Q_3 \) = predicted mass-flow-rate (kg/s) as a function of median number of light beam interruptions, and
- \( L \) = median number of light beam interruptions.

When the LED system was placed before the capacitor, the relationship between mass flow and the number of interrupted light beams was very poor (\( R^2 = 6.4\% \); data not shown). The low response of the LED emitter-receptor to change in mass-flow-rate was probably due to the low discrimination between beams to increase, causing the normal curve associated to the histogram to shift upward or to the right, or both.

Although the mass-flow-rate ranged from 3.6 to 10.7 kg/s, the average number of beam interruptions ranged only from 9.05 to 10.70 (out of 16 light beams). There was a slight tendency for the average median value to increase with mass-flow-rate (9.33, 10.02, and 10.09 for low, medium, and high mass-flow-rate, respectively). The linear relationship with \( R^2 = 43\% \) was:

\[
Q_3 = -36.1 + 4.40L
\]

where:
- \( Q_3 \) = predicted mass-flow-rate (kg/s) as a function of median number of light beam interruptions, and
- \( L \) = median number of light beam interruptions.

When the LED system was placed before the capacitor, the relationship between mass flow and the number of interrupted light beams was very poor (\( R^2 = 6.4\% \); data not shown). The low response of the LED emitter-receptor to change in mass-flow-rate was probably due to the low discrimination between

\[
\begin{align*}
\Delta f_{exp} & \quad \text{Experimental} \\
\Delta f_{cor} & \quad \text{Estimated}
\end{align*}
\]

\[
\begin{array}{cccc}
\text{Trial number} & \text{mass-flow-rate} & \Delta f_{exp} & \Delta f_{cor} \\
\text{(kg WM/s)} & \text{(MHz)} & \text{MHz/kg/s}) & \text{(MHz)}
\end{array}
\]

\[
\begin{array}{cccc}
1 & 7.2 & 12.00 & 1.67 \\
2 & 7.2 & 10.74 & 1.49 \\
3 & 3.6 & 5.50 & 1.53 \\
4 & 10.7 & 9.78 & 0.91 \\
5 & 10.7 & 10.22 & 0.96 \\
6 & 3.6 & 3.53 & 0.98 \\
7 & 7.2 & 5.95 & 0.83 \\
8 & 3.6 & 2.02 & 0.56 \\
9 & 10.7 & 8.68 & 0.81 \\
\end{array}
\]

Table I. Summed experimental (\( \Delta f_{exp} \)) and corrected (\( \Delta f_{cor} \)) frequency drop of capacitor controlled oscillator with chopped corn in the dynamic laboratory experiment.

The other sensor used in the dynamic laboratory experiment was the capacitance controlled oscillator. When forage particles flowed between the two parallel plates, the frequency of the oscillator decreased. The difference between the control frequency (no flow) and the actual frequency was summed over each trial. This summation was expected to be proportional with accumulated mass flow. Therefore, the ratio of summed frequency drop to mass-flow-rate should be relatively constant. The original experimental data showed however a gradual decrease from trial 1 to 3 and from trial 4 to 9, and a sudden change between trial 3 and 4 (Table I). This drift in the ratio of frequency drop to mass-flow-rate reflected an experimental constraint whereby the same chopped forage particles were recycled through the blower-spout system because of limited quantities. The chopped corn tended to become finer and drier as the trial number increased. The sudden change from trial 3 to trial 4 reflected a sudden reduction in particle size after a blower jam caused grinding of an important proportion of the chopped forage in the third trial. Two linear estimators of this ratio (frequency drop over mass-flow-rate) were used to correct the frequency drop:

\[
R_{1-3} = 1.70 - 0.0694n \quad \text{(5)}
\]

\[
R_{4-9} = 1.19 - 0.0529n \quad \text{(6)}
\]

\[
(\Delta f_{cor})_n = (\Delta f_{exp})_n \left( \frac{R_0}{R_n} \right) \quad \text{(7)}
\]

where:
- \( R_{1-3} \) = estimate of frequency drop per unit mass-flow-rate (MHz/[kg/s]) for trials 1 to 3,
- \( R_{4-9} \) = estimate of frequency drop per unit mass-flow-rate (MHz/[kg/s]) for trials 4 to 9,
- \( \Delta f_{cor} \) = corrected frequency drop (MHz),
- \( \Delta f_{exp} \) = experimental frequency drop (MHz) from the capacitor-controlled oscillator, and
- \( R_0 \) = linear estimate of initial experimental frequency drop per unit mass-flow-rate (1.70 MHz/[kg/s]).
When the corrected frequency drops from Table I were analyzed against mass-flow-rate, a very good correlation (R² = 96.1%) was obtained. The relationship was:

\[ Q_4 = 0.708 + 0.523(\Delta f_{corr}) \]  

(8)

where \( Q_4 \) = predicted mass-flow-rate (kg/s) as a function of the corrected frequency drop.

The mass-flow-rate is seen to be well correlated with the “corrected” summed frequency differences. Such a correction is valid only for the specific experimental conditions. A more general correction might be developed for harvest with the capacitance controlled oscillator under a wide range of conditions. This laboratory experiment indicates nonetheless the potential for oscillation differences to be well correlated with mass particle flow.

Static laboratory experiment

As in the previous experiment, the oscillator’s frequency decreased with an increase of material between the capacitor plates. Since the experiment was static, only an average value of the frequency drop based on ten successive readings was used. The relationship observed was:

\[ \Delta f = \Delta f_b + P_0(d_s) \]  

(9)

Table II. Parameters \( b_0 \) and \( b_1 \) (kHz/kg) to estimate the frequency drop factor \( P_0 \) for the static capacitance controlled oscillator system.

<table>
<thead>
<tr>
<th>Particle length range</th>
<th>Short (0-6 mm)</th>
<th>Medium (9-18 mm)</th>
<th>Long (18-27 mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( b_0 )</td>
<td>46.7</td>
<td>-31.4</td>
<td>823</td>
</tr>
<tr>
<td>( b_1 )</td>
<td>354</td>
<td>823</td>
<td>-146</td>
</tr>
<tr>
<td>( b_2 )</td>
<td>-31.4</td>
<td>823</td>
<td>-146</td>
</tr>
<tr>
<td>( b_3 )</td>
<td>354</td>
<td>823</td>
<td>-146</td>
</tr>
<tr>
<td>( b_4 )</td>
<td>-31.4</td>
<td>823</td>
<td>-146</td>
</tr>
</tbody>
</table>

The function \( p_0 \) was approximated as a linear function of moisture content by:

\[ p_0 = b_0 + b_1 M \]  

(10)

where:

\( b_0 \) = parameter to estimate frequency drop for a specific crop and chop length (Hz/kg),
\( b_1 \) = parameter to estimate frequency drop for a specific crop and chop length (Hz/kg), and
\( M \) = moisture content on a decimal wet basis (water over total wet forage mass).

Figure 8 shows two examples of the relationship between the frequency drop and the dry matter mass placed between the plates. Parameters \( b_0 \) and \( b_1 \) vary with crop species and length of cut. Table II shows parameters estimated by linear regression for alfalfa and timothy at three lengths of cut.

With the above parameters, it is possible to estimate the mass-flow-rate or the water content when the other variable is known. For example, the timothy illustrated in Fig. 8(a) had a moisture content of 83% and medium length. The frequency drop factor \( p_0 \) was estimated as 706 kHz/kg from parameters in Table II. Therefore, a quantity of 0.050 kg between the two capacitor plates would cause a net frequency drop of about 35 kHz. For a measured frequency drop, it would therefore be possible to estimate the moisture content or the mass-flow-rate if one of these two variables is measured by another independent sensor.

These parameters can also be used to estimate the precision obtained with the capacitance controlled oscillator by comparing estimations with measured values. This was done to estimate moisture content when dry matter mass and the frequency drop are known. For alfalfa, the coefficient of determination (R²) ranged between 53 and 59% and the absolute root mean square error between 9.3 and 9.9%. For timothy, R² ranged from 74 to 78% and RMSE between 9.4 and 10.9%.

It is likely parameters would need to be estimated for each crop species. Length of cut was also an important factor as shown by the estimated parameters in Table II. Data from different stages of maturity were used to generate the parameters in order to make them independent of specific growth conditions and harvesting time. A higher initial frequency than the one used for the oscillator (880 kHz) might also improve the sensitivity of the frequency drop as a function of moisture content by
further minimizing the displacement of free charges present in the forage within a measurement period. This would reduce the relative influence of other factors such as species, maturity and chop length. Further study is required to understand the relationship between oscillation frequency drop, dry matter flow, and water flow in a capacitor.

CONCLUSIONS

1. In a field experiment with chopped whole-plant corn, the impact force measured against a hinged plate in the spout of a forage harvester was well correlated with the mass-flow-rate ($R^2 = 94.8\%$). A vertical displacement transducer located at the feedrolls was also well correlated ($R^2 = 93.7\%$) with mass-flow-rate after signal filtering.

2. In a laboratory experiment with chopped whole-plant corn, the median number of interrupted beams from an LED emitter-receptor was not sensitive to changes in the mass-flow-rate. A two-plate capacitor with an oscillator (880 kHz) showed a linear drop of the oscillator's frequency as the mass-flow-rate increased ($R^2 = 96.1\%$ after a correction procedure).

3. The drop in frequency of a capacitance controlled oscillator increased linearly with mass and the slope was related to moisture content. A number of calibration parameters would be required to cover a broad range of crop species, maturities and chop lengths.

ACKNOWLEDGEMENTS

The authors express their appreciation for the financial contribution of Agriculture and Agri-Food Canada (AAC) through its Matching Investment Initiative of the Sainte-Foy Research Centre and of Dion Machineries of Boisbriand and Innotag of Beloeil, QC. Financial support also was provided by the Conseil des recherches en pêcheries et agroalimentaire du Québec. Long term support from the Natural Science and Engineering Research Council of Canada, through its research grant program, is also acknowledged. Authors thank Professor Roger Thériault for advice, Martin Roberge, Éric Morel, Sébastien Descôteaux, and Dominic Marcotte for technical assistance with the equipment and experimentation, and Patrick Lemire and Anne-Marie Tremblay for assistance with editing.

REFERENCES


