A Simulation Model of an Alfalfa Hay Yield Monitoring System on the Square Baler

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ABSTRACT
Before fabrication of any system, development of its simulation model can improve designer's understanding about strengths and weaknesses of the system. As a result, fabrication phase can be done without trial and error method. In this study a simulation model for alfalfa hay yield monitoring system on the baler was developed. Simulation of the yield measuring section led to the numerical solution of a first order differential equation. Dead reckoning method was used for simulation of the coordinates determination section. According to the results of this study: In the model of yield measuring section, the retardation time was shown. This retardation time is considered to take into account the required time for reaching crop from the ground to the baling channel. There were jagged shapes in the simulated data which coincide with changes in type of data variations. Therefore when the measured data faced a sudden change, a jagged shape will result in the simulated data. It was recommended to use each bale bulk density measuring system on the baler. In order to increase the accuracy of the coordinates determination section, it was essential to use ballast or spring pressure on the ground wheel.

Keywords: Yield monitor, Simulation model, Baler

INTRODUCTION
Development of a simulation model prior to the fabrication of any system can promote designer's view about the system. Thus development of simulation models was considered by designers of the yield monitoring systems too (Birrell et al., 1996). (Blackmore and Moore, 1999; Reyniers and De Baerdemaeker, 2005). The majority of these models simulated crop flow in the combine (Searcy et al., 1989; Reitz and Kutzbach 1996; Lark et al., 1997; Maertens et al., 2001; Arslan and Colvin, 2002). In combine harvester, crop which is fed to it is not threshed and cleaned in one stage, thus simulation model of the crop flow in the combine is more complicated than the baler and led to the solution of a differential equation with higher orders than 1. There were some reports on the fabrication of baler's yield monitoring system (Wide and Auernhammer, 1999; Marchant et al., 2002; Shinners et al., 2003; Maguire et al., 2007). In the majority of these systems,
which were built on the large balers, crop yield was monitored by the increase of baler chamber's weight, using load cells. However, in the literature review, there was no report on the simulation of crop flow through baler. Thus, in this study, because of the steady and non-parallel flow of crop in the square baler, first order differential equation was used for the simulation of yield measuring section of the yield monitoring system and simulation of the coordinates determination section was done by the ground rotated wheel method. According to the developed model some of the system’s strengths and weaknesses can be found.

** MATERIALS AND METHODS **

*Crop flow model for the small square baler*

Crop volume on the small square baler’s yield monitoring system, was measured (with calculating R, S and θ factors where R, S and θ were star wheel radius (dm), cross section of the baler output channel (dm²) and angular rotation of the star wheel (rad), respectively and converted into mass according to the crop bulk density, thus flow model can be used to relate the measured crop by the yield monitoring system and what was fed to the baler. This model should also have the ability to move yield data according to the time required for displacement of the crop from the ground to the yield measuring section. The crop flow model developed in this study was based on the principle which is schematically shown in Figure 1.

Some assumptions were used to illustrate the crop flow in this model:

1- Virtual chamber has a fixed cross section
2- Height of the crop in the chamber (h) is time dependant
3- Output flow (which is defined as $m_{out} = \frac{dm_{out}}{dt}$) was controlled by the output port using the equation below:

$$m_{out} = f(h)$$ (1)

Equation 1 demonstrates that the output mass flow is a function of crop height in the chamber. If the function is defined linear we have:

$$m_{out} = kh$$ (2)

On the other hand because input mass flow is equal to the summation of output mass flow and crop mass accumulation rate, we have:

$$\frac{dm_{in}}{dt} = \frac{dm_{out}}{dt} + \rho \frac{dh}{dt}$$ (3)

Where $A$, $\rho$ and $\frac{dh}{dt}$ are cross sectional area of the chamber, crop bulk density and variation rate of the crop height in the chamber, respectively.

Differentiation from equation 2 results:

$$\frac{d}{dt} (m_{out}) = k \frac{dh}{dt} \rightarrow \frac{dh}{dt} = \frac{1}{k} \frac{d}{dt} (m_{out})$$ (4)

Substitution $\frac{d}{dt} (m_{out})$ in equation 3 gives:

$$m_{in} = m_{out} + \rho A \frac{dh}{dt} = m_{out} + \rho A \frac{1}{k} \frac{d}{dt} (m_{out}) \rightarrow \rho A \frac{d}{dt} (m_{out}) + m_{in} = m_{in}$$

Because the dimensions of $k$, $\rho$, $A$ are $\frac{M}{LT}$, $\frac{M}{L^3}$ and $L^2$, thus the dimension of $\frac{k}{\rho A}$ can be earned:
Therefore $\frac{\rho A}{k}$ is the time constant of the model. If $\frac{\rho A}{k}$ is considered as $\tau$, final equation can be earned:

$$\frac{d}{dt}(m_{out}) + \frac{1}{\tau} m_{out} = \frac{1}{\tau} m_{in}$$  \hspace{1cm} (7)

According to equation 7 and figure 1, if output mass flow and the equation of the simulation model are known, input mass flow can be earned and vice-versa. To convert equation 7 to a function that can be solved numerically, numerical differentiation should be used. If $m_{in}$ and $m_{out}$ are denoted by $X, Y$, respectively. We have:

$$\frac{d}{dt}(Y) + \frac{1}{\tau} Y = \frac{1}{\tau} X$$  \hspace{1cm} (8)

By using the Second Order Backward Difference formula for 1st Derivative (SOBDF1D), $\frac{d}{dt}(Y)$ at time $i$ can be written according to the function $Y$ at times $i$, $(i-1)$ and $(i-2);

$$\frac{d}{dt}(Y)_i = \frac{Y_{i+2} - 4Y_{i+1} + 3Y_i}{2\Delta t}$$  \hspace{1cm} (9)

Substitution equation 9 to 8 gives:

$$Y_{i+2} - 4Y_{i+1} + 3Y_i = \frac{1}{\tau} X_{i+2} \rightarrow$$

$$X_{i+2} = Y_i + \frac{\tau}{2\Delta t} (Y_{i+2} - 4Y_{i+1} + 3Y_i)$$ \hspace{1cm} (10)

(i-2) is selected as the index of X to apply retardation time equal to $2\Delta t$ for output flow related to input flow (Experiments showed that it takes two seconds to reach crop from the ground to the yield monitoring section and because the sampling frequency of the yield monitor was 1Hz i.e. $\Delta t$= 1second, output flow is delayed from input flow by $2\Delta t$). As previously discussed the yield monitor measures crop volume which is converted to mass regarding to the crop bulk density, thus bulk density measurement’s error discloses its effects as a coefficient in equation 10. Therefore if $\mu$ and $y$ are defined as the accuracy of the bulk density measurement and the crop volume flow measured with the yield monitor, equation 10 can be rewritten as follows:

$$X_{i+2} = \mu (y_i + m(y_{i+2} - 4y_{i+1} + 3y_i))$$  \hspace{1cm} (11)

If the time constant is considered as its mathematical definition (Time constant is defined as the time required by the model to reach to 63% of its final value for response to a step increase), $\tau$ is equal to $0.63\Delta t$ and $m$ becomes 0.315. It is also possible to relate crop input flow to bale formation rate.

Output mass flow = bale formation rate × bale volume × bale bulk density  \hspace{1cm} (12)

If bale bulk density, bale volume and bale formation rate are shown as $\rho$, $V$, and $N$ we have:

$$\dot{m}_{out} = V \rho N$$  \hspace{1cm} (13)

Substitution equation 13 to 7 gives:

$$\frac{d}{dt}(V \rho N) + \frac{1}{\tau} V \rho N = \frac{1}{\tau} \dot{m}_{in}$$  \hspace{1cm} (14)

In this equation input flow is related to bale formation rate. The merit of this equation is that knowing the bale formation rate which is measured with the division of baler forward velocity by the distance between successive bales, one can simulate input flow without fabrication of the baler yield monitoring system. A program was written in C programming language to solve equation 11.
Simulating model of the coordinates determination section

Harvested alfalfa is located on the ground in parallel swaths before baling, thus coordinates can be determined according to what is depicted in Figure 2:

![Diagram](image)

Figure 2. Location determination using the dead reckoning method

As can be seen the second point coordinates can be earned knowing the first point coordinates and the distance traveled by the baler in two successive sampling intervals and the third point coordinates can be earned from the second one and so on. To realize measurement of traveled distance, the ground rotated wheel concept is suitable. In this method traveled distance can be calculated with multiplying ground wheel angular rotation by the wheel radius. After calculation of the first swath coordinates, width between two swaths was added to the last coordinates to earn the first coordinates of the second swath. It can be understood that the wheel slip and the variation of wheel diameter are two possible source of error in this model.

Fabrication of the ground wheel as a rigid body can omit the effect of wheel diameter variations, thus for simulation of the coordinates determination section a model was used that its inputs were number of ground wheel revolutions \(N\), wheel slip, direction of motion in parallel swaths which is defined by a sign (+ for one direction and – for the other) and \(y\) coordinate. The model’s output was the simulated coordinates. Equation 15 shows the model’s formula:

\[
(X_i, Y_i) = ((X_{i-1} \pm p \times k \times N), Y_i) \quad (15)
\]

Where \(p\) is the conversion factor of the wheel angular rotation to distance \(p = \pi \times \text{ground wheel diameter}\), \(k\) is the slip factor \((k=1- \text{ground wheel slip})\) and \(N\) is number of ground wheel revolutions in two successive sampling intervals. This calculation was carried out numerically with the aid of the C programming language.

RESULTS AND DISCUSSION

Evaluation of the yield measuring unit’s simulation model

To study the effect of simulated flow variations (the model’s output) related to input (measured) flow variations, some data were given as the measured flow to the model and its response was considered. These data included step, ramp and second order variations at three accuracies for bulk density (B.D.) measurement i.e. 100, 90 and 80%.

The results are depicted in Figure 3:
Figure 3. Effects of B.D. measurement accuracy and variations of the measured data on the simulated data.
The shapes of the graphs in Figures 3 suggest that the measured responses can be modeled as a first order system response and can be simulated using a first order flow model such as the one developed in this study. It is known that the baler transports material through various forms of conduits and this takes time. This means that a disturbance at the input will not be observed at the output until the material has had time to progress through the machine. Fig 3 depicts that the actual hay flow rate entering the baler could only be measured accurately for approximately 2 seconds after picking the hay swath up. That is, although the actual flow rate was for example 1 kgs$^{-1}$, this magnitude could not be measured by the yield sensor for about 2 seconds. As a result of careful observation of the experimental graphs, one can conclude the following: a constant flow rate input at the beginning of a harvest operation can not be measured by the yield sensor immediately, which necessitates the flow signal to be shifted back in time in accordance with the time delay. Initial flow rate readings do not give accurate information on the magnitude of the hay flow rate until the hay flow signal reaches its constant value, which is another critical problem that the researchers would like to address in their efforts in generating accurate crop yield maps. The model seems to explain the experimental results quite satisfactorily. The result of applying the equation 7, however, to a step, ramp and second order input functions proved to be useful. The model was able to simulate actual hay flow sensor responses obtained previously. The model was able to simulate actual hay flow responses of the sensor that were obtained previously. Thus regarding to Figure 3, it can be concluded that:

a) In all cases of crop yield variations, retardation time is shown. If abrupt changes between step, ramp and second order functions are neglected, in the case of B.D. measurement accuracy of 100%, with retarding output (simulated) data by two seconds the simulated flow completely coincides with the measured flow. This retardation time is considered to take into account the required time for reaching crop from the ground to the baling channel.

b) There are jagged shapes in the simulated data which coincide with changes in type of data variations. Because the simulated data were obtained by a numerical method, the last three measured data affect each simulated data. Therefore when the measured data faced a sudden change, a jagged shape was resulted in the simulated data.

c) With increasing bulk density measurement’s error, difference between simulated and measured flow increased. Thus it can be concluded that it is not suitable to use a fixed crop bulk density to convert volume data to mass. Therefore the crop bulk density should be measured according to a detailed basis (i.e. bulk density of each bale). As a result, adding the bale bulk density measuring unit on the baler should be considered to increase the accuracy of the yield measuring section.

Evaluation the simulation model of the coordinates determination unit

In order to evaluate the coordinates determination model, some data were given to the model as the input data and its output (simulated coordinates) were earned and compared to the actual coordinates. For these data, three levels of wheel slip were considered (0, 5 and 10%). The obtained results are shown in figure 4:
Figure 4. Effect of the ground wheel slip on the coordinates determination section

The general trend which can be seen is that with increasing the ground wheel slip, retardation of the simulated coordinates from the actual ones increased. Thus in order to increase the accuracy of the coordinates determination section, the
ground wheel slip should be decreased. Therefore it is suggested to use ballast or spring pressure on the ground wheel axle. In this study, because the used wheel was rigid and the distance between swaths was measured manually, the effects of wheel radius variation and error in length measurement were not considered. However, in yield monitoring systems which pneumatic ground wheel is used and the distances between swaths are obtained automatically, related errors must be considered in the application of the model.

Program for modeling of the yield measuring section

```c
#include <stdio.h>
#define n // NUMBER OF INPUT DATA //
#define m // COEFF. FOR SOLVING MODEL //
#define t // COEFF. FOR NUMERICAL INTEGRATION //
#define mu // COEFF. FOR B.D. MEASUREMENT ACCURACY //

void main (void)
{
    int i,j;
    float X[n];
    double S=0;
    double Y[n] =
    { //DATA MUST BE ENTERED HERE USE "," FOR DATA SEPARATION //
    }
    for(i=2;i<(n+1);i++)
    {
        // NUMERICAL EQUATIONS FOR SOLVING MODEL AND INTEGRATION //
        X[i-2] = mu*(Y[i] + m*( 3*Y[i] - 4*Y[i-1] + Y[i-2]));
        S+=t*X[i-2];
    }
    for(j=0;j<(n-2);j++)
        printf("X[%d] IS EQUAL TO %4.3f\n",j,X[j]); // PRINTING OUTPUT DATA //
    printf("\n");
    printf("ACCUMULATED MASS IS %f\n",S); // PRINTING ACCUMULATED MASS //
}
```

Program for modeling of the coordinates determination section

```c
#include <stdio.h>
#include <math.h>
#define n // NUMBER OF POINTS //
#define m // CONVERSION COEFF. FROM ANGLE TO LENGTH //
#define k // CORRECTION COEFF FOR WHEEL SLIP //
```
#define h                      // CORRECTION COFF. FOR Y COORDINATE ERROR //
void main(void)
{
    int i,j;
    int p=0;
    double D[n]={0};                         // C[n] & D[n] ARE Y COORDINATE MATRIXES //
    double A[n]={0};                        // X COORDINATE MATRIX //
    double B[n-1]=                            // WHEEL ANGULAR ROTATION MATRIX //
        // ANGULAR DATA MUST ENTER HERE USE ",," FOR DATA SERARATION //
    double C[n]=
        // Y COOR. DATA MUST ENTER HERE USE ",," FOR DATA SERARATION //
    for (i=1;i<n;i++)                        // X & Y COORDINATES CALCULATION //
        if (C[i]!=C[i-1])
            p=p+1;
        A[i]=A[i-1]+ pow((-1),p)*m*k*B[i-1];
        D[i]=h*C[i];
    }
    printf("(X[i],Y[i])\n");
    for (j=0;j<n;j++)                                  // PRINTING NEW DATA //
        printf("(%4.3f,%4.3f)\n",A[j],D[j]);
}

REFERENCES


