A weighing system for local yield monitoring of forage crops in round balers

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Abstract

Precision farming requires yield maps of all harvested crops. In order to monitor the yield of forage crops a round baler has been equipped with a weighing system. It was based on a load cell in the drawbar coupling and strain gauges in the axle. Tests were first carried out in static mode; the weights of bales could be determined with errors of less than 1%. Afterwards the suitability of the system for weighing on-the-move was examined. With signal smoothing methods spurious oscillation in the signals could be eliminated. Further investigations are necessary for reducing the remaining errors of up to 10%. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

Crop yield maps are a necessity for site-specific crop management. They allow a crop producer to identify and quantify yield variations within a field and therefore provide a basis for implementing and evaluating site-specific crop management strategies.

Recent research work for crop yield monitoring has mainly focused on the combine harvester. Different types of sensors for grain have been developed. The established models measure the grain mass via the impact of the grain flow on a plate or fingers, through the volume determined with paddle wheels or photoelectric...
guards (measurement of grain heap height in elevator) or sense the mass directly with radiometric-based systems (Vansichen and De Baerdemaeker, 1991; Borgelt and Sudduth, 1992; Auernhammer et al., 1993; Perez-Munoz and Colvin, 1996).

Despite the importance of forage production (e.g. a 50% share on the farmland with a high production level in Germany), there are no well developed yield monitoring systems for the various forage harvesting machines. Investigations were carried out with trailed type and self-propelled forage harvesters (Auernhammer et al., 1995; Missotten et al., 1997). Rottmeier (1996) and Behme et al. (1997) worked on determining the yield in round balers. They employed weighing systems for measuring the weight of a bale in the baler. For weighing in static mode they detected errors of up to 10%; weighing on-the-move led to even higher deviations.

The various yield measurement systems on combines show a much higher accuracy than the weighing systems so far developed for round balers (Kormann et al., 1998). Unfortunately the principles of the sensing devices on combines are not suitable for round balers. Volumetric-based systems require a relatively constant crop material density or a continuous density measurement. But for grass, hay or straw the density is very variable and a density detecting system is difficult to put into practice. Impact-based system are not useful, because stalks, which are joined together, falsify an impact measurement. Also, the conditions for radiometric-based systems are adverse. In contrast to the combine harvester the cross-sectional area of the mass flow in the round baler is much larger. This would require a very large radiation source and detecting unit. In addition to the high cost of such a system, general concerns about the usage of radioactive radiators have to be taken into consideration.

Due to the importance of round balers for forage production and the lack of an appropriate yield sensor, the objective of our work was to test a yield measurement system for this type of machine.

At present the principle of weighing the bale in the baler shows the best approach for a forage yield monitor. Therefore, based on the results from Rottmeier (1996) improvements for a strain gauge-based weighing system should be derived.

After installing the measuring equipment the new system requires calibration and testing for static mode weighing in the laboratory and in the field. Then factors which influence the results and the accuracy for weighing on-the-move should be determined.

2. Instrumentation and calibration

2.1. Instrumentation

For monitoring the yield by weighing, a round baler (John Deere 5501) was equipped with appropriate measurement devices (Fig. 1).

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1 Trade names are provided for the benefit of the reader and do not imply endorsement or preferential treatment of the products by the authors or the Technical University of Munich.
Due to the errors of up to 10% which Rottmeier (1996) detected for measuring the drawbar load with strain gauges, a commercial load cell (Bongshin 2000 DBC) was employed instead. It was precalibrated (1 mV corresponds to 1 kg), its measurement range extended from 0 to 2000 kg; the stated accuracy was 0.1%. This temperature compensated load cell was integrated into a redesigned drawbar coupling of the tractor (Fendt 306 LSA) employed. With the special design side forces and torsion do not influence the measurements.

The load detection on the axle was carried out via shearing strain measurements, because in contrast to the bending stress detection this type of force measurement should not be affected by point of application of force, tensile stress or compressive strain. For this task strain gauges (Hottinger Baldwin XK 11K 3/350, measurement range 2000 µm) were applied at both ends of the axles. Before their installation grooves were machined in the axle to decrease the cross-sectional area from 15.2 to 10.0 cm². This increased the shearing strain in this member and therefore the output signal of the strain gauge. The sensors were applied as full bridges. With these Wheatstone bridge circuits the low-level signals could be increased and temperature effects eliminated. The bridge supply voltage was 10 V. With an amplifying circuit the raw signals (maximum 20 mV) were amplified up to 5 V.

An A/D converter board (Analog Devices RTI-834H-32, 12 bits resolution) plugged into a heavy duty PC (Kontron IPLite 486) acquired all weight data. The data from the individual sensors were separately measured and saved on the hard drive of the PC. Since no anti-aliasing filters were used for acquiring the

![Diagram of sensors for weighing in the round baler.](image-url)
signals, the sampling rate was set to 200 samples/s with the assumption that this high rate would minimize aliasing effects in the gathered data.

2.2. Calibration

Because the load cell in the drawbar coupling was already precalibrated a calibration had to be carried out only for the strain gauges in the axle. For this task a platform was installed in the baling chamber of the baler where weights could be applied. The actual load on each side of the baler’s axle was registered with two platform scales (maximum error < 0.1%) which were placed under each wheel of the baler.

For calibrating, a maximum of 900 kg, in increments of 60 kg, was placed on the platform in the baling chamber and the output voltages from the sensors were registered (Fig. 2). The measured output voltage $V_D$ was related to the applied weight $x$ by:

$$V_D = 1.0012x + 0.15$$

The calculated coefficient of determination ($R^2$) was 0.9999.

3. Static weighing

Static weighing was carried out in the laboratory and in the field. In the laboratory the accuracy, hysteresis and reproducibility of the weighing system were investigated. In the field the system was tested during regular usage of the round baler.
3.1. Laboratory tests

As for the calibration the weights were loaded on the platform in the baling chamber. But this time the weight values were registered for the unloading, too. The procedure of loading and unloading was carried out four times. Afterwards the differences between the applied weights and the measured values for all replications were determined and the 95% confidence intervals CI were calculated (Figs. 3 and 4).

3.2. Field tests

In the field finished bales were weighed with the round baler weighing system. With the vehicle stopped a measurement of the baler with the finished bale was taken before (gross weight) and after the removal of the bale (tare weight). The baler was not moved between these two measurements. All the bales were re-weighed with a crane scale (maximum error < 0.1%) on the front loader of a tractor. This weight information served as a reference.

Fig. 5 shows an example of bale weights measured with the round baler weighing system and their deviations from the reference bale weights for a hay crop from a meadow (‘Grafwiese’) with 1.5 ha.

The bale weights have an average deviation of −0.4 kg and a standard deviation of 1.43 kg. For approximately 75% of the bales, the errors amounted to at most ±1 kg. The relative weight deviations were correspondingly low with

![Graph](image-url)
a range of less than ±1, and 75% of the weight errors lay within ±0.5%. This accuracy is dependent on the fact that the baler is not in motion during weighing and is not moved between the gross and tare weight measurements.

4. Dynamic weighing

4.1. Weight signal characteristics

When the weighing is performed during driving, the weight signal is overlaid by spurious oscillations caused by the unevenness of the ground and machine vibrations (Fig. 6). Between 0 and 6 s the tractor was not moving, but its engine was running and the PTO was turned off. Distinct oscillations were visible already. As soon as the PTO was turned on (after 6 s), the amplitude increased considerably. When the baler started moving (after 23 s) the amplitude of the oscillations greatly increased. Maximum deviations of more than 700 kg occurred.

The results of a frequency spectrum analysis show mainly oscillations with low frequencies and significant differences between the drawbar coupling and the axle (Fig. 7). The dominant frequencies detected at the drawbar coupling chiefly extend from 0 to about 10 Hz, at the axle they range from 0 to approximately 4 Hz. The amplitudes of the oscillations at the axle are much higher than at the drawbar coupling.
4.2. Weight signal processing

Based on the signal characteristics the weight signals were processed. To eliminate noise and yet not reduce the responsiveness of the system a Butterworth low-pass filter with a cut-off frequency of 0.1 Hz was chosen.

The capabilities of a bandpass filter are reduced if a signal has a large proportion of non-periodically created oscillations. This proportion is indicated by the amplitude for 0 Hz in the frequency spectrum. Fig. 7 shows an amplitude of 6 kg at 0 Hz for the weight signals measured at the drawbar coupling and 25 kg for the signals which were registered at the axle. A spline approximation is not affected by non-periodically created oscillations. Therefore a spline approximation (cubic spline) was chosen as an alternative noise reducing method. In contrast to bandpass filtering, a spline approximation requires much more calculation. Based on other results (Wild, 1998) the 'weight factor' a parameter which determines the smoothness of a spline was set to 0.01.

4.3. Testing of the smoothing methods

The suitability of both smoothing methods was investigated with the help of a swath with gaps (Fig. 8). Each swath section had the same weight (57.1 kg) which was determined with a portable platform scale (maximum error < 0.1%) before baling. An attempt was made to distribute the crop (grass silage) in each swath section equally. The gaps served as main inspection areas for errors because the

![Fig. 5. Bale weights measured with the round baler weighing system and their absolute deviations from the reference bale weights (Grafwiese, 29 June 1995, static weighing).](image)
weight of the bale in the baler while passing through the gaps was known from the platform scale measurements (reference weight). The appearance of the raw data was similar to that shown in Fig. 6. The deviations reached several hundred kilograms; the gaps in the swath were not recognizable in the course of the signal.

Fig. 6. Weight signals measured at the drawbar coupling and at the right side of the axle while producing a bale.

Fig. 7. Frequency spectrum of the weight signals measured at the drawbar coupling and at the right side of the axle (tractor speed, 6.2 km/h; engine revolution, 35 Hz; PTO revolution, 9 Hz).
The low-pass filter and the spline smoothing led to a marked reduction of the unwanted noise in the signal (Fig. 9). The calculated weights of the bale in the baler are shown. The gaps in the swaths are recognizable as plateaus in the run. The low-pass filter and the spline curve show a very similar course.

The deviations of the low-pass filtered weight signals to the weights which were measured with the platform scale are highly variable (Fig. 10). The figure shows the error range in the individual sections for the low-pass filtered weight signal. All calculated errors range over ±20 kg. The largest range was from −16 to +15 kg and falls in the area immediately in front of the swath, whereas in the other positions the range is essentially lower. In the gaps, the registered deviations between the expected values and the measured values range from a few kilograms up to 20 kg.

![Diagram](image-url)  
**Fig. 8.** Swath with gaps for determining weighing errors with dynamic measurements.

![Diagram](image-url)  
**Fig. 9.** Smoothed registered weight signal from the round baler (low-pass filter, cut-off frequency, 0.1 Hz; spline, weight factor, 0.01).
Fig. 10. Deviations of the low-pass filtered signal from the reference weight in the swath with gaps.

Similar error values are also apparent on the weight curve, which resulted from the spline smoothing (Fig. 11).

Larger differences between the two noise eliminating procedures become visible in the throughput curves (Fig. 12). In the diagram the processed signals from the beginning to the end of the swath with gaps are shown. The throughput curve based on the spline is clearly smoother than that produced by the low-pass filtering. It
shows a much lower frequency and the deviations from the reference throughput are much smaller.

4.4. Non-oscillation based errors

Additional investigations were carried out to detect the causes of weighing deviations which are based on non-oscillation effects. A trial length was examined in the meadow with the empty baler (constant weight, no pick-up of crop), and after every 4 m, the vehicle was stopped and the static weight was read. Therefore all dynamic influences were excluded. The measured weighing errors are shown in Fig. 13. Their ranges extend from \(-17\) to \(+15\) kg. The absolute magnitude of these errors is similar to the weight deviations determined for the swath with gaps. Therefore it is obvious that the applied filter and smoothing techniques remove almost all oscillation based deviations. Further tests showed that the remaining errors were caused by parameters such as the point of application of force influencing the shearing strain measurements in the axle with strain gauges (Wild and Auernhammer, 1997; Wild, 1998). Those errors did not occur at the drawbar because at that location the load cell with the special drawbar coupling was employed.

4.5. Accuracy of dynamic weighing in regular field operations

For the existing operation in the Grafwiese the weights of the bales were also registered via dynamic weighing. With the determined throughput data the weights of the finished bales were calculated (Fig. 14). The absolute errors of the bale
weights range from about $-60$ to $+20$ kg with an average error of $-10.5$ kg (standard deviation 19.4 kg). The average relative error was $-2.8\%$ (standard deviation 5.1%). Approximately 75\% of the values were between $-5$ and $+5\%$, and two values were outside $\pm 10\%$. A later investigation found that the predomi-

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**Fig. 13.** Deviations from the actual weight on a test path in the meadow.

**Fig. 14.** Absolute and relative deviations from the reference bale weights (Grafwiese, 29 June 1995, dynamic weighing, weight data smoothed with spline approximation).
nantely negative values were caused by a mix-up of the calibration factors for the axle strain gauges. When the corresponding calibration factors were adjusted, all the errors were within ±10%.

4.6. Improving the accuracy for dynamic weighing

Compared to yield sensors in a combine harvester the deviations of ±10% for a yield measurement system in a round baler are very high. These errors are caused by non-oscillation effects which interfere with the measurements from the strain gauges on the axle. Therefore the influences of parameters like point of application of force at the axle have to be reduced.

A simple measure for reducing the interferences would be the application of narrower tires which would decrease the influence of the lever arm. But this is critical in the assessment of higher ground compression. Another possibility would be the replacement of the shearing strain measurement with a double bending stress determination (‘difference measurement’). For this detection two sets of strain gauges are applied closely together. The difference between the signals provided by the two sensors is used for the weight determination.

On the round baler tested a difference measurement could not be employed due to the machine design. The difference measurement with two sets of strain gauges requires more space than the shearing stress detection with one set which was not available. Therefore, if new harvesting machines are developed, the design should take the application of weighing sensors into consideration.

5. Conclusions

The static weighing of bales in the round baler has been shown to be a suitable procedure for yield determination. Weighing during vehicle stops could be carried out with errors of less than 1%. This means a major improvement compared to the existing systems. The technical capability for weighing with this accuracy is provided by strain gauges in the axle and by a load cell in the drawbar coupling.

With the weights of finished bales local yield monitoring can be carried out. However, the maximum geographical resolution of yield maps is limited to the size of the area from which a bale was produced. Additionally, the field operation is interrupted for gaining the static weight data. Therefore weighing on-the-move is desirable.

Weight measurements on-the-move are disturbed by dynamic effects. Spurious oscillations in the weight data can be greatly decreased with low-pass filters or spline approximations. Despite the signal smoothing, weight deviations of 10% remained. They are caused by non-oscillating effects which falsify the weighing with the strain gauges in the axle. Therefore further investigations are required for eliminating this source of errors.
References


