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Design and Experiments of the Data Acquisition System for Bale Rolling Characteristic Parameters on a Large-Scale Round Bale Machine

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Abstract: The parameters of the roll characteristics of a large-scale round bale machine were collected in real time to investigate the bale rolling mechanism. This investigation develops a set of adaptable and highly integrated data acquisition systems for the bale rolling performance parameters of large-type round bale machines. A rolling experiment is conducted using sunflower straw as the material, and the power consumption and radial tension of the roller-round bale machine during the bale rolling process are studied. In the grass core formation stage, the round bale machine's torque need was minimal, the radial tension of the bale remained nearly constant, and the bale chamber was primarily filled with loose sunflower straw. The motor torque and the straw bale's radial tension both showed a tendency of gradual increase when the round bale machine was in the grass-filling stage. The motor torque and bale radial tension displayed a roughly linear trend of rapid rise as the sunflower straw continued to enter the rolling bale chamber; this was when the round bale machine was in the compressed bale rolling stage. When the power consumption of the round bale machine was measured using the data acquisition system during the test bench empty run and core-creation stage, the energy consumption comparison analysis produced a relative error of 5.8%. During the stage of bale rolling and compression, the data acquisition system monitored the power consumption of the round bale machine. The relative error was 9.5%. The data acquisition system of the round bale machine test bed has an accuracy of 90.5%–94.2% when measuring the machine's power consumption, indicating that it is a stable and efficient system. This study provides a foundation for further research on intelligent the roller-round bale machine.

Keywords: round bale machine; bale rolling characteristics; straw bale; data acquisition; power consumption; radial tension

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1. Introduction

Crop straw, a renewable biomass energy source, can be used to produce biomass for power generation, compost, and feed livestock. Using crop straw not only alleviates environmental pollution but also has economic value [1–4]. It is divided into round and square balers due to different working principles and bale shapes. In contrast to the rectangular bale machine, the round bale machine has the advantages of low equipment cost, the good natural rainproof effect of straw bales, an easy maintenance of the machine, no need to tie knots, etc., which has made the round bale machine widely used [5,6]. The baler's bale rolling parameters (bale rolling power consumption, bale rolling density and bale size) are the key indexes for evaluating the performance and working condition of the baler. Therefore, it is of great importance to obtain the parameters of bale roller characteristics in real-time to keep it, which not only can guide the driver to complete the

straw bale baling operation efficiently but also can indirectly improve the comprehensive utilization rate of straw and the ecological environment [7–9].

Several scholars have studied the performance measurement and control system of round balers [10–13]. Xie et al. [14] designed a measurement and control system for loading and unloading bales of round bale machines, optimized each functional component's structure and motion parameters, and effectively improved the working efficiency of key elements. Xiao et al. [15] designed a set of measurement and control systems based on PLC as the core, which realized the precise control of the number of baling and netting circles. Zhao et al. [16] conducted a study on the feeding device of the round bale machine, installing a displacement sensor in parallel to the hydraulic cylinder for monitoring; they also installed two pressure sensors on the oil path of the rodless and rodded chambers of the hydraulic cylinder, respectively, to monitor the change in oil pressure in the process of roll pressure. Some scholars used the method of laying radio resistance strain gauges on steel rolls and ANSYS simulation to study the change rule of radial force in the process of roll compression and established the compression model and stress relaxation model [17]. Yin et al. [18] found a weighing calculation model for the rolling and sliding phases of the hay bale in response to the problem that the density of the rolled bale in the round bale machine is difficult to measure in real time. A monitoring system based on slant contact pressure, attitude angle measurement and the hydraulic cylinder was constructed, and the accuracy of the weighing model was verified. Loftis et al. [19] designed a system for measuring bale weight and investigated the reliability of the test system by correlating the uniaxial response with bale weight for specific bale diameters. Shang et al. [20] developed an automatic internet control system with a remote monitoring function and tested it in the laboratory and the field. To avoid false alarms caused by the vibration of the end plate of baling, a time filter was designed in the system. The controller sends the baling operation parameters to a remote monitoring terminal via RS232, forwards the work track, bale and work area to a server, and receives commands from the server to turn the control system on or off. A U-shaped rod instead of a straight rod was designed at the opening of the bundling chamber, and an S-shaped tension sensor was installed between the U-shaped rod and the hook to obtain roller pressure data during the bundling process [21]. The parameters collected by the measurement and control system of bale rolling characteristics of the round bale machine are relatively single, failing to reflect the change rule of the radial tension of the straw bale in real-time. For the objectives of research, most of the grass, corn, rice straw, etc., are substituted for hard straw (sunflower straw).

The round bale machine is the research object in this article, and a data acquisition system based on LabVIEW 2020 software is designed to capture the rolling characteristic parameters of the system. The radial tension and power consumption of the roller-round bale machine during the bale rolling process are examined in this rolling experiment, which uses sunflower straw as the material. The roller-round bale machine's data acquisition system's dependability for the bale rolling characteristic parameters is confirmed. This study provides a foundation for further research on intelligent roller-round bale machines.

2. Materials and Methods

2.1. The Construction of the Round Bale Machine Test Bench and the Analysis of the Bale Rolling Process

2.1.1. Construction of the Round Bale Machine Test Bench and Working Principle of Bale Rolling

The round bale machine test bench mainly consists of a rear roll bundling chamber, a front roll bundling chamber, an unloading oil cylinder, a bundling mechanism, a pick-up device, a conveying device, a control system, etc. It mainly has functions such as conveying, picking up, feeding, rolling bundles, alarming, bundling, unloading, and data collection and storage, as shown in Figure 1. Specific parameters can be found in Appendix A, Table A1. With the conveyor belt's running in conjunction with forward movement, the picker's bullet teeth pick up the straw on the surface of the conveyor belt. After being fed into the bale chamber by the toggle, the straw is rotated into straw cores under the

action of the rotating steel rollers. With continuous picking and feeding, the straw will wrap around the outer circumference of the bale, forming a round bale that is tight on the outside and loose on the inside. When the grass bales reach a certain density, the hydraulic system alarms, and the tying rope is stopped. After the unloading oil cylinder opens, the warehouse door is opened to complete the unloading of the rope [22,23].

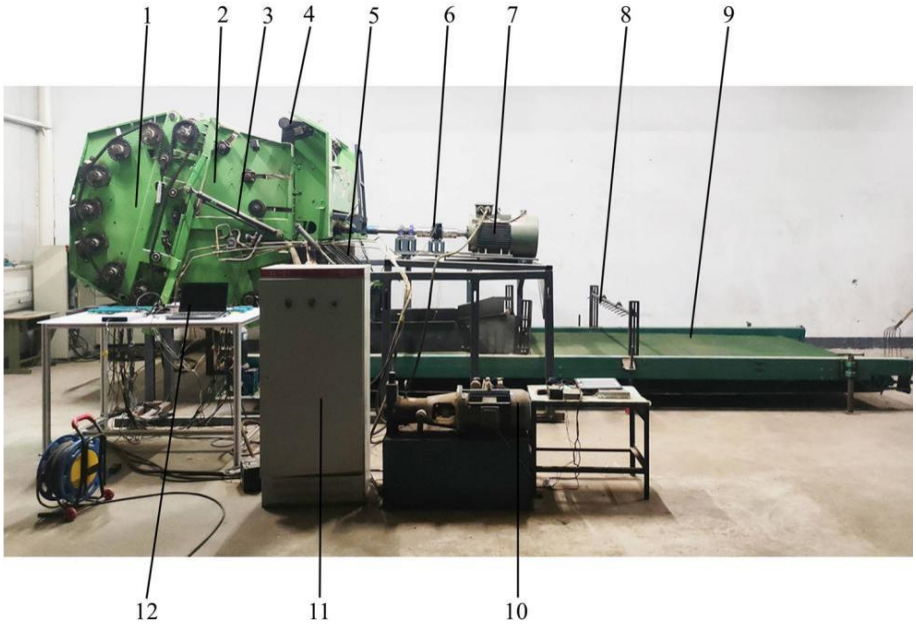


Figure 1. The round bale machine test bench. 1. Rear roll bundling chamber; 2. Front roll bundling chamber; 3. Unloading oil cylinder; 4. Bundling mechanism; 5. Pick-up device; 6. Torque sensor; 7. The motor; 8. Grass equalizer; 9. Conveying device; 10. Hydraulic system; 11. Control system; 12. Data acquisition system.

2.1.2. Analysis of the Bale Rolling Process in the Round Bale Machine

The round bale machine's movement procedure can be examined to determine that the bale formation process can be broken down into three steps, as depicted in Figure 2. The straw puller sends the straw to the rolling and bundling chamber once the pick-up device raises it to a predetermined height. The rolling and bundling room has two side walls and steel rollers arranged around the perimeter. In the grass core formation stage, the straw is twisted around revolving steel rollers. As the amount of straw increases, it gradually fills the rolling and bundling chamber, forming round grass bundles. This is the grass-filling stage. The bale is compacted continuously and reaches a certain density, creating a bale with a tight surface layer and a loose core, completing a rolled bale; this is the bale rolling compression stage [24].

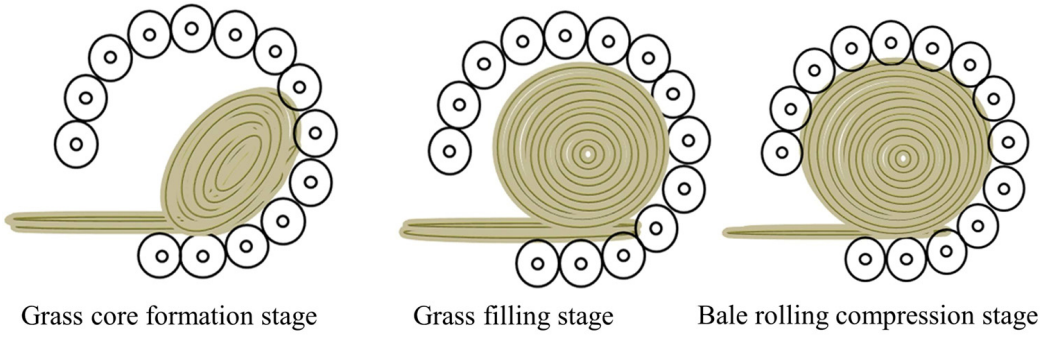


Figure 2. Analysis of the bale rolling process.

2.2. Design of the Hardware System

2.2.1. Hardware System Design for Bale Radial Tensioning

The straw will appear to act as a force as the straw and straw squeeze against each other and the straw husk and pith embrace each other during the bale rolling process. Surface tension is the force acting on the straw bale. The only tension that the steel rolls above the center of the straw bale are subject to during bale rolling is the radial tension of the bale. On the other hand, the steel rolls situated beneath the center of the straw bale are susceptible to both the radial tension and the gravitational force of the bale. Sunflower straw is a viscoelastic body with elasticity and other mechanical characteristics, and it is difficult to collect the radial tension of round straw bales continuously in real time using traditional methods. In this experiment, the top five-steel rollers were selected as the tested steel rollers to monitor the situation of straw material filling the bundling chamber in real time. In an ideal state, the radial tension of the straw bundle on the steel rollers above the center of the bundling chamber is considered a uniformly distributed load, which is equal in magnitude to the radial reaction force of the steel roller and opposite in direction. During the rolling process, the roller bearing always rotates towards a specific location on the bearing seat because of the compression between the steel roller and the grass bundle. A reaction force is created on the bearing seat support by the steel roller's radial reaction force acting on the bearing seat through the bearing [25]. Consequently, the steel roller assembly is reduced to a "simply supported beam" in accordance with the design of the round bale machine, and the radial tension of the bale on the steel roller is ascertained by calculating the support reaction force of the bearing seats at both ends of the five-steel roller during the bale rolling process. Figure 3 illustrates the arrangement of the S-type tensile pressure sensors (101S; Lianji, Anhui, China) at either end of the five-steel roller. On either end of the bearing seat of the steel roller, a single bearing support reaction force measurement device is positioned along the radial direction of the grass bundle. While the other end of the pressure sensor is threaded to the measuring rod and fits through the homemade bearing housing's through-hole to rest against the outside surface of the bearing's outer ring, the other end of the sensor is attached to the frame. The force measurement direction of the sensor points directly to the center of the bale circle, and the measuring column is adjusted so that a certain preload exists between the bearing and the force sensor. This allows the radial tension of the bale to be recorded in real time while the round bale machine is rolling the bale.

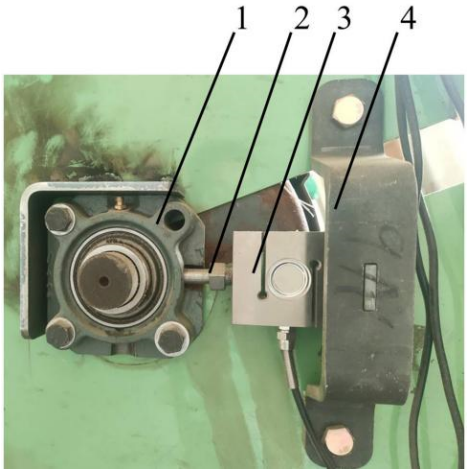


Figure 3. Bale radial tension sensor deployment. 1. Bearing seat; 2. Measurement column; 3. S-type tensile pressure sensor; 4. Sensor Support.

2.2.2. Hardware System Design for the Round Baler Torque

To collect the instantaneous torque and instantaneous rotation speed values of the power input motor of the round bundle, a torque sensor(JN-DN3; Jinnuo, Anhui, China) is

deployed between the motor's output shaft and the round bundle's power input shaft, as shown in Figure 4.

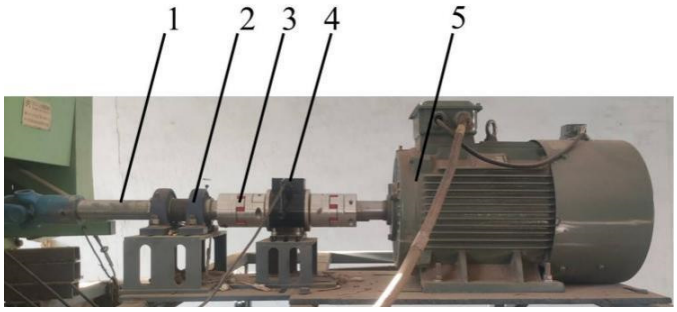


Figure 4. Torque sensor deployment. 1. Drive shaft; 2. Seated bearing; 3. Shaft connection; 4. Torque sensor; 5. Motor.

2.2.3. Design of the Overall Hardware System

The project team has already calibrated various sensors in the early stage [26,27]. The torque sensor (JN-DN3; Jinnuo, Anhui, China) counts the torque and rotation speed of the motor, the rotary encoders(E6B2 cwz1x; OMRON, Kyoto, Japan) counts the speed at which the steel rollers rotate, and the S-type tensile pressure sensors (101S; Lianji, Anhui, China) measures the radial tension of the bale during rolling. The signal lines of each sensor are connected to the terminal block, and then the terminal block is connected to the data acquisition card (USB-6363; NI, Austin, TX, USA) through a shielded cable and finally connected to the computer to complete the hardware part of the whole acquisition system, as shown in Figure 5.

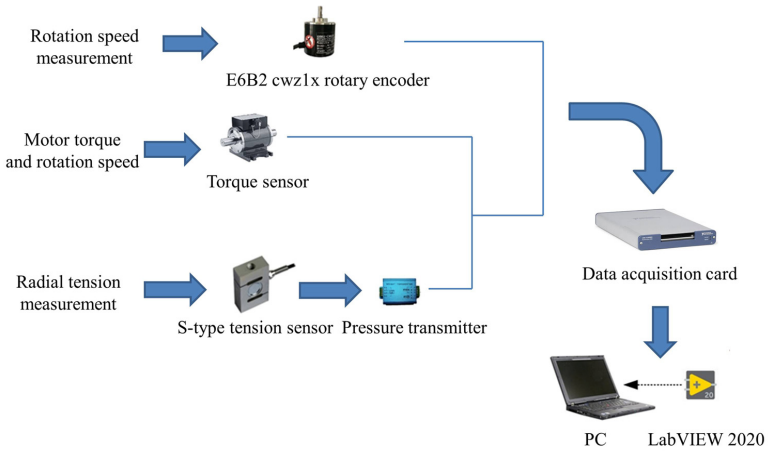


Figure 5. Data acquisition system schematic diagram.

2.3. Design of the Software System

The round bale machine roll bundle operation site vibration, noise interference, and electromagnetic interference are strong. Therefore, the acquisition card requirements are high, and the data acquisition, calculation, display, storage, etc., must be considered, so the data acquisition card (USB-6363; NI, Austin, TX, USA) was chosen. The data acquisition card is capable of plug-and-play, high-speed and stable transmission. This test is based on the NI USB-6363 external data acquisition card and LabVIEW 2020 (NI, Austin, TX, USA) to write the acquisition of torque sensors (JN-DN3; Jinnuo, Anhui, China), S-type tensile pressure sensors (101S; Lianji, Anhui, China), rotary encoders (E6B2 cwz1x; OMRON, Kyoto, Japan) and other upper computer acquisition programs. There are a total of 20 analogue voltage signals and 4 pulse signals. A total of 24 physical channels need to be created, and analogue channels need to be assigned to each channel. The voltage

range is set to −10 V to 10 V, and the terminal configuration is single-ended input. The sampling clock source and sampling rate are set up for signal channel assignment, and the physical channel configuration interface is shown in Figure 6. During the testing process, the non-standard electrical signals collected by the sensor must first be converted into standard electrical signals or current signals. The standard voltage signal transmitted to the acquisition card is transformed into a digital signal through A/D conversion and sent to the PC through a USB data cable. The NI-DAQmx of the upper computer completes the communication of the serial port and the reception of data and then analyzes the data to complete the collection, display, and storage.

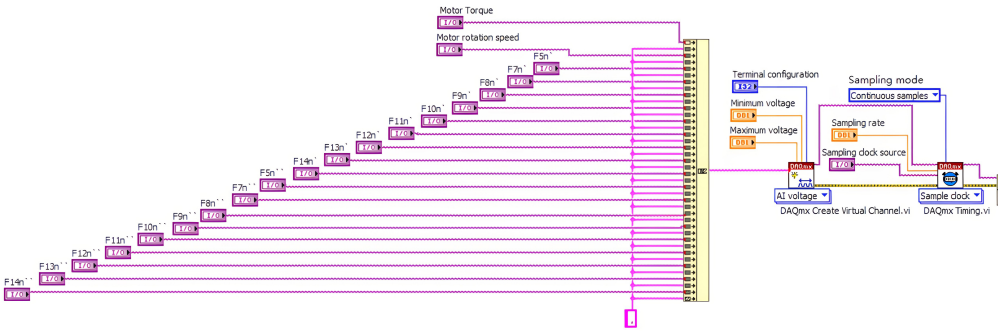


Figure 6. Physical channel configuration view for each sensor.

2.3.1. Bale Radial Tension Acquisition Program Design

The support response force of the bearing seats at both ends of the rollers was measured during the bale rolling process in order to determine the radial tension of the bale on the steel rollers. To write the bale radial tension collection program, the representative five-steel roller above the bale's center is chosen as an example; the other rollers are comparable. As determined by the force sensors at both ends, the radial tension of the bale with respect to the five-steel roller is equal to the algebraic sum of the support reaction forces of the bearing seats. During installation, a preload force F_{Pre} is applied to ensure the measurement cylinders are tightly fitted to the bearings. S-type tensile pressure sensors (101S; Lianji, Anhui, China) on each steel roll were systematically calibrated, and the equation of the calibration fitting curve was $F = kU_{in} + m$. The fitted curve for the five-steel roller was $F = 1.032U_{in} - 25.664$. The bale radial tension acquisition program is shown in Figure 7. The system saves all the data in CSV. format to the computer for the further processing and analysis of the test data.

$$F = 2(kU_{in} + m - F_{Pre}) \quad (1)$$

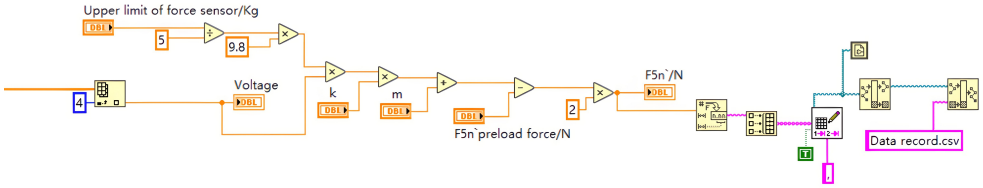


Figure 7. Bale radial tension acquisition program.

In the formula: F is the radial bale tension (N). U_{in} is the voltage value (V) of the radial force sensor. k is the calibration factor of the force transducer (k_5 = 1.032 N/V). m is the calibrated intercept of the force transducer (m_5 = 25.664 N). F_{Pre} is the preload force for installing the force transducer (N).

2.3.2. Program Design for Torque, Rotation Speed and Power Consumption of Round Baler Motor

The torque sensors (JN-DN3; Jinnuo, Anhui, China) has a torque measurement range of 0~1000 N·m, an output voltage of 0~5 V, and a linear correspondence of Y = 200×. The

rotation speed measurement range is 0–1000 r/min, the output voltage is 1–5 V, and the linear correspondence is Y = 250× − 250. The passed array is parsed out as the current voltage value according to the order in which the channels are set. The actual parameters can be obtained through linear conversion and then displayed by the display control and the waveform; the other programs are designed according to this principle. The collection program for motor torque, motor rotation speed, instantaneous power consumption, and total power consumption of the circular bundling machine is shown in Figure 8.

$$P_i = \frac{T_i \times n_i}{9550} \quad (2)$$

$$W_i = P_i \Delta t \quad (3)$$

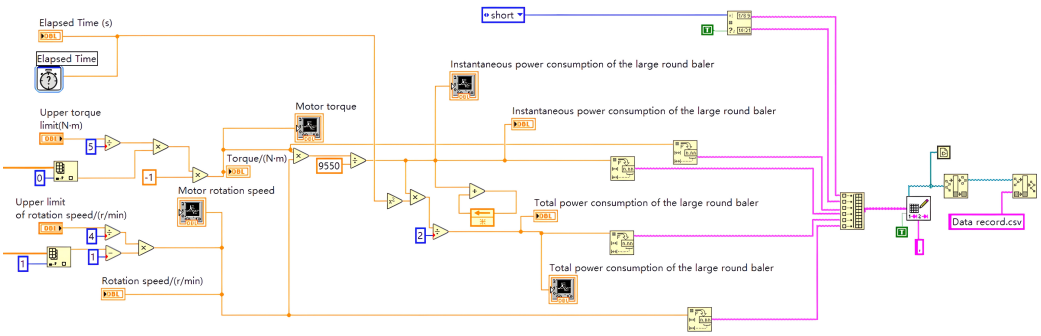


Figure 8. Torque, rotation speed, power, and power consumption acquisition program.

In the formula: T_i is the instantaneous torque of the circular bundling machine motor collected for the i-th time (N·m); n_i is the instantaneous rotation speed of the round bale motor collected at the i-th time (r/min); P_i is the instantaneous power of the round bale motor collected at the i-th time (kW); W_i is the total power consumption of the round bale machine (kJ); Δt is the interval time (1 s) between acquisitions by the acquisition system.

2.3.3. Program Design for Rotation Speed

The pulse of the rotary encoder(E6B2 cwz1x; OMRON, Kyoto, Japan) is 500 P/R, which means 500 pulse signals are emitted for each revolution. The rotation speed acquisition program for steel rollers, conveyor devices, etc., is shown in Figure 9.

$$n = \frac{60L}{500} = \frac{3L}{25} \quad (4)$$

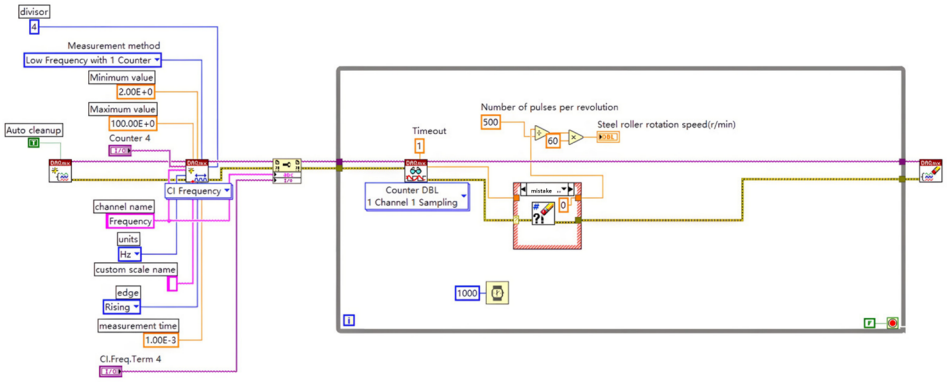


Figure 9. Rotation speed acquisition program.

In the formula: n is the collected rotation speed, r/min; L is the number of collected pulses.

2.3.4. The Data Acquisition System of Bale Rolling Characteristic Parameters of the Large-Scale Round Bale Machine

The front panel of the data acquisition system of bale rolling characteristic parameters of the large-scale round bale machine consists of a title area, a parameter setting area, and a data display area, as shown in Figure 10. The collection channels and sensor measurement parameters are all located in the parameter setting area. The data display area can display dynamic data such as the radial tension of grass bales, motor torque and rotation speed, steel roller rotation speed, and power consumption of the round bundling machine. During the experiment, real-time parameter changes can be viewed separately by clicking different tab labels.

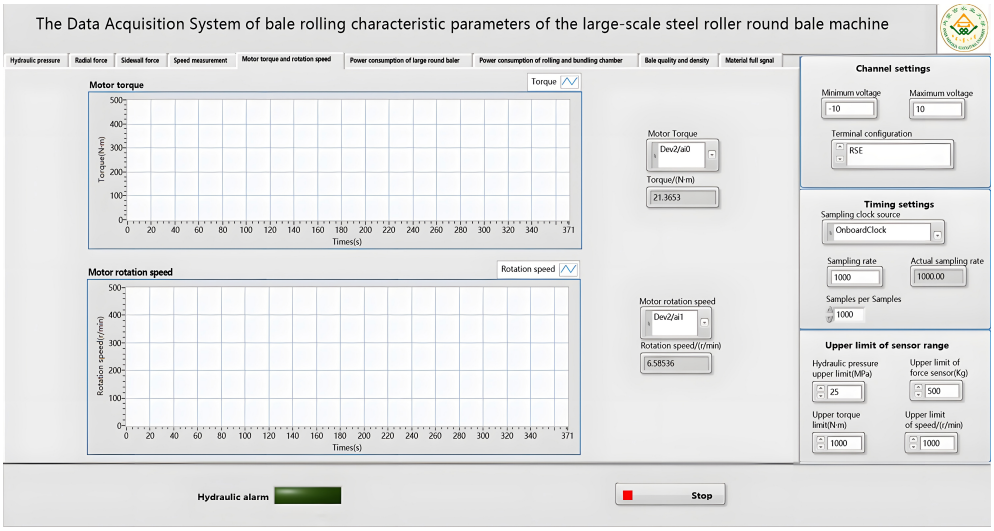


Figure 10. Front panel of the data acquisition system of bale rolling characteristic parameters of the large-scale round bale machine.

2.4. Validation Test

Sunflower straw (species Sunflower 1013), which was collected from Wuchuan County, Hohhot City, Inner Mongolia Autonomous Region, China (40°80′ N, 111°20′ E), was used as the test material. Straw length is 1600–1800 mm and stem thickness is 18–25 mm. The straw was truncated to 500–600 mm length to facilitate the subsequent straw rolling test. The moisture content of the straw was determined to be 20% using the drying method, as shown in Figure 11.

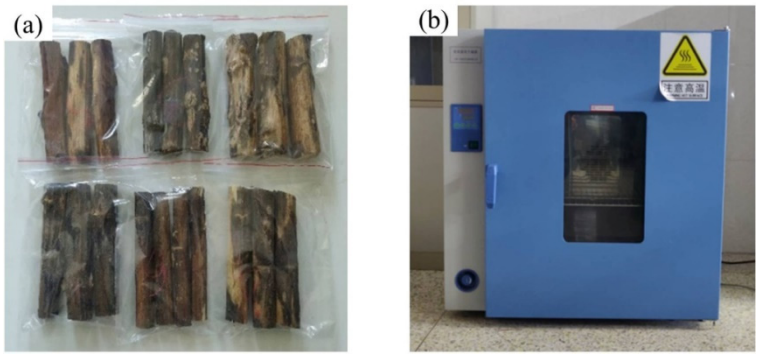


Figure 11. Measurement of straw moisture content. (**a**) Sunflower straw; (**b**) drying of straw, seen from front panel.

The experiment was conducted under uniform feeding conditions, with the steel roller linear speed and belt feeding speed set to 1.8 m/s and 0.2 m/s, respectively, using the two frequency converters mentioned above. Each experiment lasted 180 s, with the

round bundling machine empty running for 10 s, and 150 s from the start of feeding to the cessation of rolling and bundling. The remaining 20 s were the static time for the grass bales. The sunflower straw moving and bundling test is shown in Figure 12. An electric energy meter was installed at the input of the drive motor of the round bale machine to measure the electric energy consumed by each group of sunflower straw rolled bales during the test process and to verify it using the data acquisition system.



Figure 12. Sunflower straw rolling bale test.

3. Results and Analysis

3.1. Analysis of the Bale Rolling Characteristic Parameters

The curves of the bale radial tension, motor torque and speed with time are shown in Figures 13 and 14. The motor torque increased slowly during 10–70 s, while the bale radial tension was small and almost constant. This means that the sunflower straw in the bale chamber room is generally loose, that the torque needed for the round bale machine to work is minimal, and that the sunflower straw did not come into contact with the five-steel rollers during the construction of the grass core. In the range of 70 to 80 s, there was a gradual increase in both the motor torque and the bale's radial tension. This shows that the entire bale chamber had been filled with sunflower straw, forming the molded bale and completing the grass-filling stage. After 80 s, the sunflower straw continued to enter the bale rolling chamber for the bale rolling compression stage, exhibiting a roughly linear and rapidly growing trend in the motor torque and bale radial tension. This demonstrates the dependability of the data collecting system and correlates with how the round bale machine actually operates.

The data acquisition system measures the instantaneous power consumption values of the round bale machine, and the power consumption value of the round bale machine is monitored via the power meter; the change curve of the power consumption is shown in Figure 15. The maximum power consumption is about 15.49 kJ when the test bench runs empty (0–10 s). Power usage climbed progressively as the sunflower straw was fed into the bale chamber gradually until straw filling (80 s) during the core creation and material filling stage. The round bale machine required 214.51 kJ of power. The molded bale rotated quickly under the operation of each steel roller during the bale rolling and compacting stage while the straw material continuously entered the bale rolling chamber. A linear and swiftly increasing trend could be seen in the round bale machine's power usage. The round baler has a maximum power consumption of roughly 1143.22 kJ.

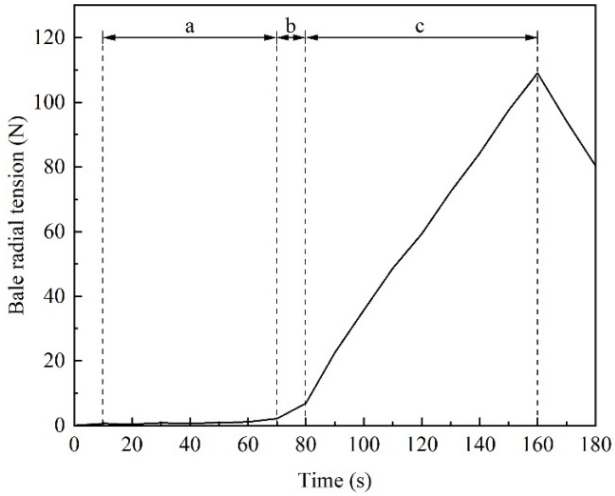


Figure 13. Bale radial tension variation curve. a—Grass core formation stage; b—grass filling stage; c—bale rolling compression stage.

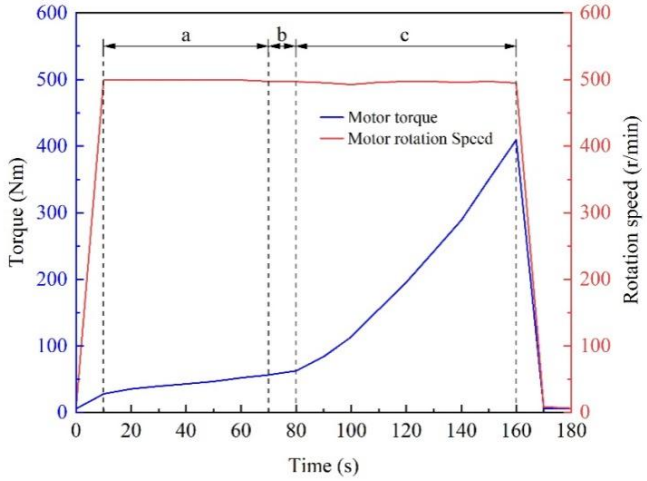


Figure 14. Motor torque and speed variation curves. a—Grass core formation stage; b—grass filling stage; c—bale rolling compression stage.

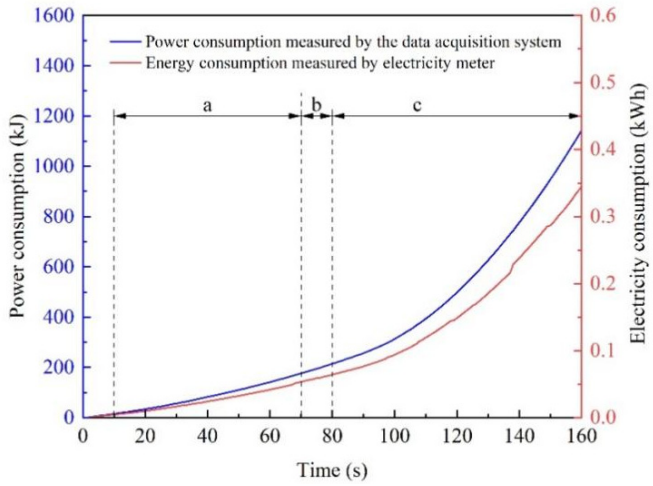


Figure 15. Variation curve of round baler power consumption. a—Grass core formation stage; b—grass filling stage; c—bale rolling compression stage.

The data curve is modified through the comparison and analysis of the energy meter monitoring the electrical energy of the round baler, which is depicted in Figure 15, and the power consumption was recorded using the data acquisition system. The conversion relationship between power consumption and energy consumption during the test bench empty rotation stage and the grass core formation stage led to the calculation that the relative error of the power consumption of the round bale machine, as measured using the data acquisition system, was 5.8%. Throughout the bale rolling and compression cycle, the data gathering system recorded a 9.5% relative inaccuracy in the power usage of the round bale machine. According to the test results, the round baler's power consumption may be accurately determined within the range of 90.5% to 94.2% using the data gathering system of the round baler test bench. The data collecting system of the round bale machine test bench is demonstrated to be reliable and efficient and it offers a theoretical framework for the machine's cleverly innovative design. However, the source of the experimental error is that sunflower straw is a hard material and vibration occurs which affects the accuracy of the collected data during the rolling process.

3.2. Discussion

In this paper, a set of highly integrated and flexible data collecting systems for large-type round bale machines' bale rolling performance metrics was designed, based on the LabVIEW 2020 software platform. In the course of bale rolling, it can record and show real-time statistics on power consumption, rotation speed, motor torque, and bale radial tension. The test demonstrated that the radial tension of the bale was minor and remained nearly constant, the round bale machine's torque need was minimal, and the bale chamber was mostly filled with loose sunflower straw during the grass core-creation stage. The radial tension of the straw bale and the motor torque of the round bale machine both had a slow, increasing trend throughout the grass-filling stage, indicating when the sunflower straw had been filled to the brim with the fullu rolled bale chamber. The motor torque and bale radial tension exhibit a roughly linear trend of rapid growth as the sunflower straw keeps moving into the rolling bale chamber. The round bale machine was in the compression stage of rolling bales. This demonstrates the dependability of the data collecting system and correlates with how the round bale machine actually operates. The data acquisition system recorded the power consumption of the round bale machine during the test bench empty run and core construction stage. The energy consumption comparison analysis produced a relative error of 5.8% in this measurement. Throughout the bale rolling and compression cycle, the data gathering system recorded a 9.5% relative inaccuracy in the power usage of the round bale machine. The round bale machine test bed's data collecting system is reliable and efficient, as evidenced by the accuracy of the machine's power consumption measurement, which ranged from 90.5% to 94.2%.

Fang J.J. measured the radial tension of grass bales during the bale rolling process of a large-type round bale machine by installing a wireless resistance strain gauge on a steel roller above the rear bundling chamber [28]. Although this measurement method meets the conditions for directly measuring the force between the steel roller and the grass bundle, the measurement process is intermittent and not continuous; the measurement method in this article can continuously collect the radial tension of grass bales in real time, and the measurement results provide a basis for the optimization design of the steel roller structure. This article mainly provides a dynamic measurement method for the real-time radial tension and power consumption of grass bales during the bale rolling process of the large-type round bale machine. However, the power consumption is affected by various factors, such as material moisture content, feeding amount, material uniformity, and test equipment performance. For different test conditions and test equipment, its reliability needs to be further studied.

4. Conclusions

(1) This paper designed a set of highly integrated and flexible data collecting systems for the large-type round bale machines' bale rolling performance metrics, based on the LabVIEW 2020 software platform. In the course of bale rolling, they can record and show real-time statistics on power consumption, rotation speed, motor torque, and bale radial tension.

(2) The test demonstrated that the radial tension of the bale was minor and remained nearly constant, the round bale machine's torque need was minimal, and the bale chamber was mostly filled with loose sunflower straw during the grass core-creation stage. The radial tension of the straw bale and the motor torque of the round bale machine both had a slow, increasing trend throughout the grass-filling stage, indicating that the sunflower straw had now been filled to the brim with the fully rolled bale chamber. The motor torque and bale radial tension exhibit a roughly linear trend of rapid growth as the sunflower straw keeps moving into the rolling bale chamber. The round bale machine was in the compression stage of rolling bales. This demonstrates the dependability of the data collecting system and correlates with how the round bale machine actually operates.

(3) The data acquisition system recorded the power consumption of the round bale machine during the test bench empty run and core construction stage. The energy consumption comparison analysis produced a relative error of 5.8% in this measurement. Throughout the bale rolling and compression cycle, the data gathering system recorded a 9.5% relative inaccuracy in the power usage of the round bale machine. The round bale machine test bed's data collecting system is reliable and efficient, as evidenced by the accuracy of the machine's power consumption measurement, which ranged from 90.5% to 94.2%.

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Appendix A

Table A1. The performance parameters of the large-type round bale machines.

Project	Parameter	Value
Baling room	Baling room diameter/m	1.2
	Width of baling room/m	1.5
	Number of steel rollers	14
	Pressure range of the unloading cylinder/MPa	0~16
Conveyor device	Working length/m	6
	Effective working width/m	1.5
Motor	Rated power of the electric motor of the round bale machine/kW	13
	Rated power of conveyor motor/kW	4

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