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Development and Test of Grain Mass Flow Monitoring System Based on Pressure Sensor

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ABSTRACT

In view of the technical development requirements of digital agriculture and the requirement of operation parameter regulation in the operation process of grain harvester. An on-board grain mass flow monitoring system based on pressure sensor was developed. The mathematical model of grain mass and grain flow pressure was established, which realized the real-time measurement, display, and storage of grain dry/wet quality information during the operation of grain harvester. An indoor bench test was carried out with the independently developed grain flow monitoring test bench. The results showed that the output error of the grain mass flow monitoring system was less than 4.25% under the conditions of indoor bench test, which meets the accuracy requirements of grain flow monitoring and provides the decision basis for variable seeding and variable fertilization.

Keywords: Flow monitoring; Pressure sensor; Monitoring system; Grain flow; Digital agriculture

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Introduction

Grain mass flow monitoring is the basis of grain harvester yield measurement technology. Real-time monitoring of grain flow is easy to get information about grain yield and farmland, and get the relationship between farmland environment and regional yield. It provides decision-making basis for variable seeding and fertilization, and provides data and technical support for the full implementation of digital agricultural technology [1-2].

At present, grain quality flow monitoring technologies mainly include various monitoring methods such as impact type, photoelectric type, and weighing type [3-4]. The impulsive flow monitoring method is the most widely used. For example, Zhou Jun et al. [5-6] developed an impact grain flow monitoring system based on the deformation principle of cantilever beam, and developed an impact grain flow sensor with a parallel beam structure. The relative measurement error was controlled within 10%. Chen Shuren et al. [7-8] designed a double-plate differential impact grain flow sensor. For the monitoring system, a calibration test bench for the grain flow monitoring system was developed, and the flow monitoring error was less than 5.4%. In order to reduce the error of machine vibration on flow monitoring, many scholars have proposed a monitoring method of installing a photoelectric sensor on the scraper grain elevator. For example, Strubbe et al. [9] studied a grain volume flow monitoring device based on a three-dimensional array optical sensor. The maximum yield measurement error is 9%. Fu Xinglan et al. [10-11] developed a grain flow metering system based on the principle of photoelectric diffuse reflection. Weighing-type grain quality monitoring devices are more intuitive to extract effective signals for production measurement. Zhang Xiaochao et al. [12] designed a spiral-propelled weighing grain quality monitoring device based on the weighing principle, and achieved good results. But the use of the need for more reaper transformation. Although the above-mentioned grain quality flow monitoring system can meet the production requirements to a certain extent, it has not been promoted and applied in China due to the constraints of monitoring principles, monitoring accuracy, and installation methods. Therefore, the development of a grain mass flow monitoring system with good versatility, easy installation and high monitoring accuracy has important practical significance for the realization of intelligent and digital agriculture.

Based on the above research, in order to improve the accuracy of the monitoring system, simplify the installation method and improve the adaptability to different crop yield monitoring, this paper designs a grain mass flow monitoring system based on the principle of grain flow pressure, and establishes the relationship between grain flow pressure and quality. The grain mass flow monitoring system performance are tested through indoor bench tests, which provide new methods and new devices for the development of grain yield monitoring.

1. Design of grain mass flow monitoring system based on pressure sensor

1.1 Overall design

The pressure type grain quality flow monitoring system (as shown in Figure 1) is mainly composed of a flow monitoring device, a height control switch of the header, a core processor, and a human-computer interaction device. The flow monitoring device is installed at the tail of the grain collection and elevator, and the grain discharged from the grain collection and elevator enters the granary after passing through the flow monitoring device. The height control switch of the header is composed of a tension sensor, a spring and a chain. The core processor and the human-computer interaction device are installed in the cab of the grain harvester.

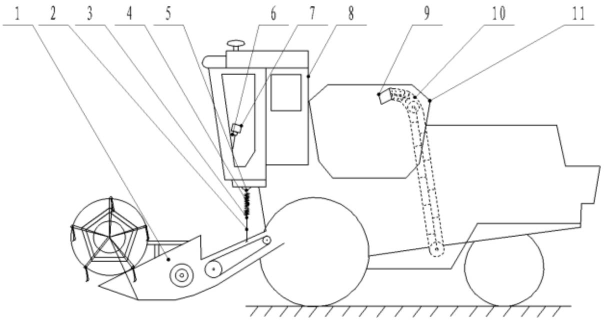

Fig. 1 Diagram of grain mass flow monitoring system based on pressure sensor
1. Header 2. Chain 3. Header height control switch 4. Spring 5. Tension sensor 6. Core processor 7. Human-computer interaction device 8. Cab 9. Flow monitoring device 10. Grain elevator 11. Granary

When the grain harvester begins the harvesting operation, the core processor detects the working status of the header through the header height control switch. When the header is working, the control system starts flow monitoring; after threshing and cleaning The grains are transported by the grain elevator to the flow monitoring device. The core processor obtains the grain flow pressure information through the pressure sensor in the flow monitoring device and converts it into a voltage signal. At the same time, the core processor obtains the average moisture content of the grain through the humidity sensor. The amplified and filtered signal constructs a grain mass flow monitoring model, calculates the grain wet/dry quality. During the flow monitoring work process, the human-computer interaction device realizes the grain dry/wet basis visual display of information such as quality and grain moisture content.

1.2 Hardware design

The hardware system can be divided into three parts: signal acquisition, data processing and data display. The signal acquisition module is mainly composed of a height control switch of the header and a flow monitoring device, which completes the acquisition of multichannel grain mass flow related sensor signals. The data processing module is composed of a core processor, which completes signal processing, calculation of grain quality related information, data communication and other functions. The data display module is composed of a human-computer interaction device, which completes the visual display of grain quality and the configuration function of various parameters.

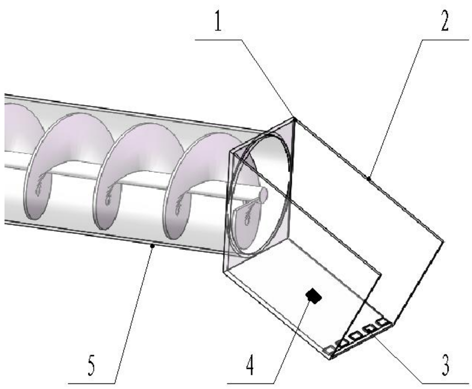

Fig.2 Grain mass flow monitoring unit
1. Flow monitoring device 2. Concave guide plate
3. Pressure sensor 4. Humidity sensor 5. Grain elevator

The flow monitoring device (as shown in Figure 2) is installed at the tail of the grain elevator. It is mainly composed of a concave guide plate, a pressure sensor, and a humidity sensor. It is used to continuously monitor the pressure of the grain flow discharged from the grain elevator.

In order to obtain the weight of the grain that passing through the flow monitoring device, the cross-sectional area of the grain flow needs to be calculated from the thickness information of the grain flow cross-sectional area. Therefore, pressure sensors were installed uniformly on the stable cross-section of grain flow, which is the bottom surface of the concave guide plate. The pressure sensors collected the pressure of the cross-sectional unit, and get the thickness distribution equation of the grain flow, then the cross-sectional area can get by integrating. In order to ensure the accuracy of the cross-sectional thickness equation, the width of the concave baffle and the production cost was considered as the influence factors. As the result, five pressure sensors were installed in this paper to obtain the grain flow pressure information. The bottom surface of the concave baffle is 10cm in length, and the horizontal inclination angle is 5° to ensure that the grain can flow out of the flow monitoring device normally, and ensuring that the pressure value obtained by the pressure sensor is approximate to the real pressure (cos 5°=0.99619 ≈1). The pressure sensor adopts the PVDF piezoelectric film sensor, which has a thickness of 52 μm, is soft in texture, and can withstand large bending deformations. In order to reduce the impact of vibration on the monitoring accuracy, EVA foam double-sided tape was added between the sensor and the bottom plate for vibration isolation. A signal conversion amplifier module was added to the system to amplify the output voltage of the piezoelectric film. The output signal range of the module is 0~3.3 V, the conversion accuracy is ±0.01 V, and the dynamic magnification is adjustable from 0 to 100 times, which can effectively improve the resolution accuracy of the system.

In order to obtain the dry basis weight of the grain flow, a grain moisture sensor was installed at the bottom of the concave deflector in the flow monitoring device to make the detection probe fully contact the grain flow. It can guarantee the calculated dry basis weight of grain can satisfy the national grain storage standard. The grain moisture sensor in the system was selected as the FDS100 moisture sensor based on dielectric theory and using frequency-domain measurement technology (FDR). The sensor has a measurement range of 0-100%, the measurement accuracy of ±1.5%, and a response time of less than 1s.

The core processor of the grain quality flow monitoring system uses the STM32F407 development board, which uses ST's STM32F407ZGT6 chip based on the Cortex-M4 core (ARMv7-ME architecture), it supports floating-point operations, and has enhanced DSP processing instructions. The core processor needs to convert the analog signal collected by the sensor into a digital signal, and it has 3 12-bit ADCs (Analog-to-Digital Converter) and up to 24 external measurement channels to meet the requirements of the multi-sensor in the grain mass flow monitoring system Information exchange needs. The STM32F407 development board comes with a standard SD card slot, the highest communication speed can reach 48 MHz, and the highest transmission data can reach 24M byte/s. It can realize real-time storage of system monitoring data, which is convenient for later data processing, query, and storage.

In order to facilitate real-time data display and system parameter configuration, the system uses a serial HMI touch screen as a human-computer interaction device. The touch screen communicates with the core processor through the serial port (USART 232) and completes the interaction with the core processor by clicking the corresponding controls in the man-machine interface.

1.3 Software design

The grain mass flow monitoring system is developed based on the MDK5 platform and uses C language to write programs to realize the collection, conversion, analysis, display, and storage of multiple sensor information during the operation of the grain harvester. Based on the consideration of portability and subsequent function expansion, a modular idea was adopted for program design, including: system initialization module, used to initialize core processor port functions, variable definitions, configuration clocks, etc. The task of self-checking module is completing sensor functions detection to ensure the normal operation of the system. The parameter configuration module is used to configure the calibration parameters, the type of harvested grain, grain weight and other information; The data processing module can collect and process output signals from multiple pressure sensors, humidity sensors, and the control switches of the cut header, and build a grain weight flow monitoring model and calculate the related information of grain weight. The data display module realizes the real-time display and refresh of grain dry/wet basis weight information, moisture content information, and the parameter setting information. The data storage module is used for the storage of monitoring data during the operation of the grain harvester, which is convenient for the later data viewing and analysis.

According to the software functional requirements of the grain quality flow monitoring system, the software working logic of the core processor is as follows: After the system starts to work, the relevant functions are initialized firstly, including analog-to-digital conversion ADC, serial port USART initialization, clock configuration, and interrupt priority setting initialized. Then checking the function of each sensor in the system, if the system has no faults, then complete the relevant parameter configuration. Otherwise, display the system fault information for fixing. Obtain the working status/height control switch information of the header, when it exceeds the set threshold, it indicates that the grain harvester has put down the header and starts the normal harvesting operation; otherwise, continue to obtain the height control switch information of the header. When it is detected that the grain harvester starts the normal harvesting operation, the information of the pressure sensor and the humidity sensor in the flow monitoring device are obtained through the ADC channel. According to the pressure information, the grain mass flow monitoring model is constructed, and the grain moisture content information obtained by the humidity sensor is combined to calculate the grain dry/wet basis quality. The system transmits the obtained grain mass flow-related data through the serial port to the human-computer interaction device for weight display. At the same time, the system will store the relevant data of the grain mass flow to the SD card until the software finishes running.

2. Grain mass flow monitoring model

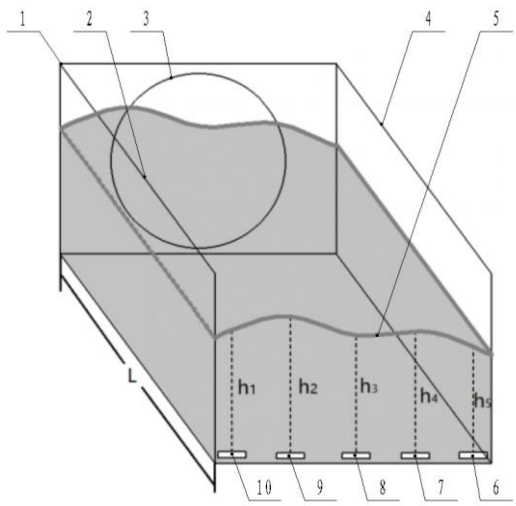

Fig.3 Schematic diagram of grain mass flow monitoring modelmonitoring device 2. The right-side wall of the concave deflector 3. The tail of the grain collection and elevator 4. The left side wall of the concave deflector 5. The cross section of the grain flow 6. The first reference position 7. The second reference position 8. The third reference position 9. The fourth reference position 10. The fifth reference position

In order to get accurate information of the grain mass flow, the grain is regarded as a special fluid and continuous medium [13-14]. A grain mass flow monitoring model is established as shown in Fig. 3.

A cross section in the width direction of the concave deflector bottom surface is selected as the sensor base, and determine multiple sensor installation positions on it (take 5 as an example). The reference is set near the left side wall of the grain flow direction in the flow monitoring device. The position is recorded as the first reference position, and the distance from the first reference position to the fifth reference position is the width of the bottom surface of the concave deflector.

The grain flow pressure information is obtained from five pressure sensors at the same time, the pressure at five reference positions are named as F_1, F_2, F_3, F_4, and F_5.

According to the formula of the fluid force on the plane in hydro statics, the height of the grain flow at the reference position can be obtained:

$$h = \frac{F}{\rho g S_a} \qquad (1)$$

In the formula, F is the pressure of the grain flow at the reference position, N; S_a is pressure sensor area, m^2; ρ is grain density, kg/m^3; g is acceleration of gravity, N/kg.

The pressures F_1, F_2, F_3, F_4, and F_5 at the five reference positions are substituted into formula (1) to obtain the grain flow thickness h_1, h_2, h_3, h_4, and h_5 at the five reference positions.

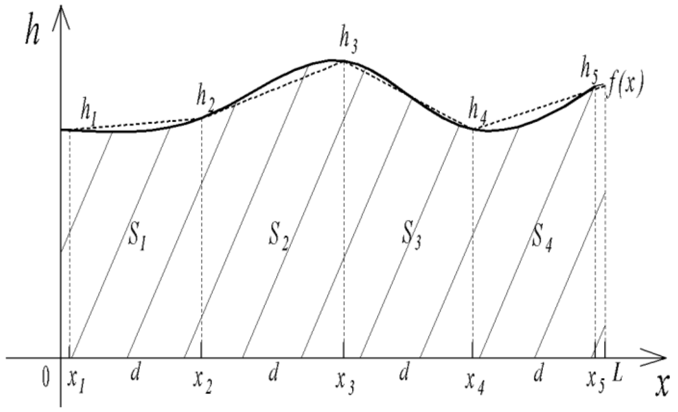

Fig.4 Coordinate system of grain flow cross section

In Fig.4, the vertical coordinate h is the grain flow thickness, and the abscissa x is the distance between the sensor monitoring position and the left side wall of the deflector. According to the above five grain flow thickness information, the grain flow thickness on the cross-section is fitted the distribution equation $h = f(x)$, then integrate the function on the interval $[x_1, x_5]$, the area of the cross-section of the grain flow can be obtained:

$$S = \int_{x_1}^{x_5} f(x)dx \qquad (2)$$

The time interval Δt is set as the data collection cycle of the pressure sensor, assuming that the grain flow velocity is stable at v (considering the grain collection process, the grain harvester is stably carrying out the harvesting operation when the grain collection elevator tail auger speed is stable, the pushing speed of grain is also constant, and the flow change can only make the change of the thickness of the grain layer), the volume formula $V = Sv\Delta t$ and the weight formula $Q = \rho V$ can get the grain weight of each collection section:

$$Q_i = \rho S v \Delta t \qquad (3)$$

In the formula, ρ is grain density, kg/m^3; S is cross-sectional area of grain flow, m^2; v is conveying material speed, m/s; t is data collection frequency, s.

It can be seen from the above formula that the shorter the collection period, the higher the accuracy of grain flow detection, but the greater the amount of information the system has to process. In order to ensure the measurement accuracy and avoid the error caused by the use of sensors to monitor the grain flow rate, the grain flow rate is calibrated. It can be seen from formula (3) that the grain density ρ and the grain flow velocity v are constant during the time interval Δt (determined by the collection frequency), so the grain flow rate and the grain flow cross-sectional area at the standard speed of the conveying auger are constant Proportional relationship，which is $Q_0 \propto S_0$。

Therefore, in the actual operation of the grain harvester, the wet base weight of the grain in each collection section of the grain weight flow monitoring system is:

$$Q_i = \frac{S}{S_0} Q_0 \qquad (4)$$

In the formula, Q_0 is calibrated grain quality, kg; S is cross-sectional area of grain flow in each collection section, m^2; S_0 is grain flow cross-sectional area under the calibration of grain weight Q_0，m^2.

From formula (4), the wet base quality of all the grains in the collection section is summed, and the wet base weight of the grains in the corresponding area can be obtained：

$$Q = \sum_{i=1}^{n} Q_i \qquad (5)$$

In the formula, Q is area grain wet base weight, kg; Q_i is grain wet base weight in each collection section, kg. The above obtained is the grain wet basis weight, and the national standard moisture content of grain storage is 13%. Combining the grain moisture content w measured by the monitoring system; the standard grain dry basis quality can be obtained by converting it：

$$Q_b = \frac{Q(1-w)}{1-13\%} = \frac{Q(1-w)}{87\%} \qquad (6)$$

In the formula, Q is the total wet base weight of cereals by area, kg; Q_i is grain moisture content, %.

3. Development trend of soybean seed-metering device in China

3.1 Grain flow monitoring test bench

In order to test the performance of the grain quality flow monitoring system, a grain flow monitoring test bed was designed (as shown in Fig.5). The test bench is mainly composed of a flow monitoring device, agitation auger, a grain inlet tank, a plug-in board, a three-phase AC motor, a reducer, a bench, etc.

The grain flow monitoring test bench is based on the prototype design of the end conveying auger of the Lovol GM80 grain harvester grain collection and elevator. The auger pitch is 112 mm, the outer diameter is 140 mm, the inner diameter is 60 mm, and the horizontal inclination angle is 5°; the auger drive motor is a three-phase AC motor with a power of 0.75 kw and a speed of 1500 r/min; a reducer RV075 with a speed ratio of 20; the capacity of the grain tank is about 0.15 m^3.

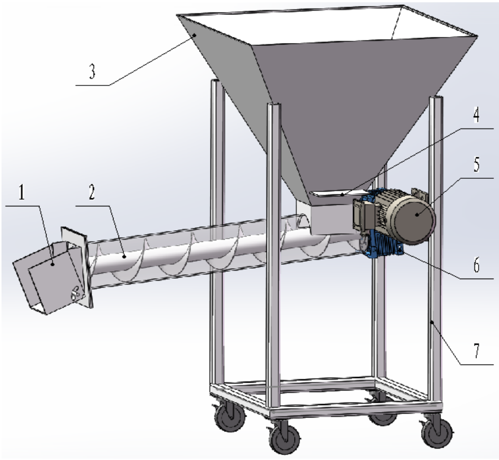

Fig.5 Experiment platform of grain flow monitoring system
1.Flow monitoring device 2. Stirring auger 3. Enter the grain tank
4. Insert board 5. Motor 6. Reducer 7. Bench

3.2 Test materials and methods

Qimin 10 wheat grains was selected as the test grain, which came from the Zibo Linzi Fuqun Agricultural Machinery Cooperative. Qimin 10 conform the basic characteristics of corn in the Huanghuaihai area. Before the test, the average moisture content of the sample was measured to be 17.63%, and the bulk density was 747 g/L.

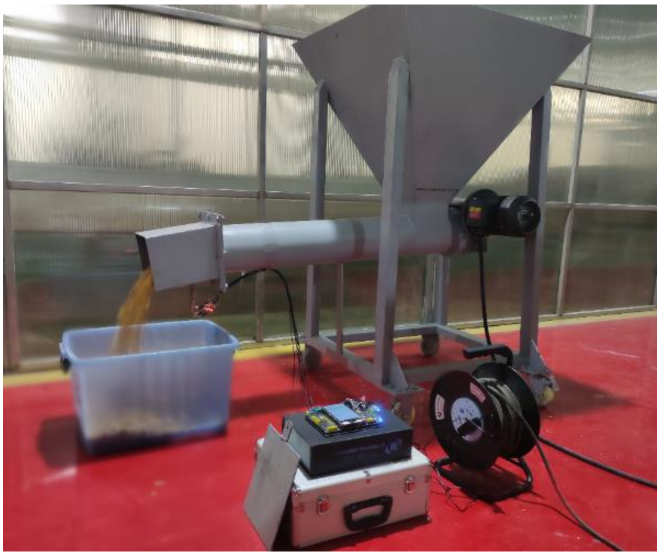

Fig.6 Photograph of testing scene

First carry out the pre-experiment, fill the grain into the grain tank, start the test bed, the standard speed of the conveying auger is 70r/min, open the test bed insert plate to 50% opening, and the test bed runs for 10s after the grain flow is stable, using the grain collection box to collect maize. At the same time, the grain mass flow monitoring system starts to monitor and counts. Stop receiving after running for a period t, and weigh the grain quality in the grain collection box, and combine the values measured by the monitoring system to obtain the standard through multiple repeated tests. The calibrated value of grain quality Q_0 and grain flow cross-sectional area S_0 under rotating speed.

During the test (Fig.6), enter the calibrated Q_0 and S_0 into the system through the human-computer interaction device to complete the parameter configuration. Fill the grain into the grain box, start the test bed, the standard speed of the conveying auger is 70r/min, open the test bed insert plate to the required opening, after the test bed runs for 10s, use the grain collection box to start receiving materials The test bench will stop receiving the maize after 100s running to reduce grain filling errors [15].

After the test, the remaining grains in the grain box and the grains flowing to the outside of the grain collection box are weighed, and the total loading weight of the grain box is subtracted from the above two parts of grain weight to obtain the actual grain weight through the grain flow monitoring device. Obtain the system monitoring values through the human-computer interaction device of the monitoring system, and calculate accuracy of the monitoring system.

The formula of grain quality measurement error is:

$$E_1 = \frac{Q_t - Q_m}{Q_t} \times 100\% \qquad (7)$$

The calculation formula for the monitoring error of grain moisture content is：

In the formula, Q_t is the actual weight of grain passing through the grain flow monitoring device during system running, kg; Q_m is the measured grain mass flow by monitoring system, kg.

$$E_2 = \frac{w_t - w}{w_t} \times 100\% \qquad (8)$$

In the formula, w_t is before the test, the national standard method was used to measure the average moisture content of the grain sample, %; w is water content monitoring value of grain production monitoring system，%.

3.3 Test results and analysis

To explore the influence of the grain feeding flow rate on the measurement accuracy of the grain mass flow monitoring system, the degree of the test bench opening was adjusted to five states of 20%, 40%, 60%, 80%, and 100%. The test was repeated 3 times with the same test material, and the test data is shown in Table 1.

Tab.1 Laboratory test data of grain mass flow monitoring system

Socket opening (%)	Test number	Water content monitoring value (%)	Water content monitoring error (%)	Actual value of grain quality(kg)	Measured output value(kg)	Production measurement error (%)
20	1	17.37	1.47	46.35	44.51	3.97
	2	17.41	1.25	46.98	48.92	-4.13
	3	17.78	-0.85	47.16	45.16	4.24
40	1	17.85	-1.25	47.16	45.77	2.95
	2	17.79	-0.91	47.27	48.96	-3.58
	3	17.49	0.79	48.13	46.67	3.03
60	1	17.44	1.08	48.05	49.25	-2.5
	2	17.48	0.85	46.81	48.71	-4.06
	3	17.83	-1.13	49.44	47.92	3.07
80	1	17.38	1.42	49.98	48.51	2.94
	2	17.83	-1.13	50.46	49.11	2.68
	3	17.46	0.96	48.77	47.23	3.16
100	1	17.51	0.68	50.71	49.53	2.33
	2	17.87	-1.36	48.95	50.44	-3.04
	3	17.47	0.91	49.86	48.39	2.95

From Table 1, analysis of the water content monitoring value of the monitoring system shows that the water content monitoring error is less than 1.5%, which meets the system design requirements. By analyzing the influence of the grain feeding flow rate on the measurement accuracy of the grain mass flow monitoring system, there is a big measurement error when the plate has a small opening degree. The reason is that the grain flow velocity is easy to be unstable when the grain feeding flow is small.

The measurement error range of the grain weight-yield monitoring system is -4.13% ~ 4.24%, and the error fluctuation is less than 4.25%. Overall, indicating that the grain quality flow monitoring system performs well under the indoor bench test conditions.

4. Conclusion

1) Established a grain mass flow monitoring model between grain flow pressure and weight, which provides theoretical guidance for the development of a grain quality flow monitoring system.

2) Developed a grain flow monitoring test bench, and developed a grain mass flow monitoring system based on the principle of grain flow pressure, and realized the real-time measurement and display of grain dry/wet basis weight information during the grain conveying process.

3) Experiments on the grain quality flow monitoring system show that the grain quality measurement error of the grain quality flow monitoring system is less than 4.25%, which meets the accuracy requirements of grain weight flow monitoring.

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