

Article

Design and Test of a Grain Cleaning Loss Monitoring Device for Wheat Combine Harvester

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Abstract: As the world's first large grain crop, wheat in its mechanized harvesting process faces a serious problem, namely, when the combine harvester operating parameters are not set reasonably, it leads to increased losses of wheat kernels to an extent exceeding the prescribed standard, of which the loss of scavenging accounts for a large proportion. Excessive grain harvest loss will not only reduce the quality of the wheat harvest but also adversely affect its yield. Real-time monitoring of losses in the harvesting process is key to the dynamic adjustment of operating parameters to decrease machine harvesting losses. This article proposes a grain cleaning loss monitoring device for combine harvesters suitable for wheat crops. It aims to measure the loss of grain cleaning in the process of wheat harvesting in real time and adjust the operating parameters of the harvester timeously by feeding back the data to the driver in real time, so as to decrease the loss of wheat grains in the process of harvesting and achieve the purpose of reducing the loss of harvest. When the device was tested in the field, the wheat variety was Bainong 4199, the yield per mu was 625.83 kg (one mu is 1/15 of a hectare, or approximately 666.67 m²), the mass of grain was 43.21 g, and the water content was 14.2%. After the test, the monitoring error of the loss monitoring device was within 8%, and the average error rate was 6.69%. The test proves that the monitoring device achieves the expected design effect and meets design requirements. The results of this paper are of significance to the intelligent control system of wheat combine harvesters and provide a reference for research into grain cleaning loss monitoring devices for wheat combine harvesters.



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Keywords: wheat; cleaning loss; monitoring; sensor; harvester

1. Introduction

As one of the world's major food crops, wheat is the world's third most common grain after rice and corn and the second most produced for human consumption [1]. As a big wheat producer and consumer, with the development of agricultural mechanization, wheat combine harvesters have benefited from rapid progress. At present, China's wheat harvesting rate has reached more than 98%.

According to the "Technical Conditions of a Full-Feed Combine Harvester" issued by the Ministry of Industry and Information Technology of China in 2017, the loss rate of wheat mechanical harvest is $\leq 1.2\%$ [2]. However, according to the survey of the research team, the postpartum loss and waste of Chinese farmers' grain remain serious, and the harvest loss rate in some areas far exceeds the national standard level.

During the mechanized harvesting of wheat, improper configuration of operational parameters can lead to an increased rate of grain loss [3]. Consequently, when confronted with elevated loss rates, it is imperative for the operator to promptly fine-tune the settings of the combine harvesters to minimize such losses.

Traditionally, the loss rate of mechanical harvesting is determined through post-harvest manual sorting, weighing, and computation. This is both laborious and inefficient, lacking in real-time capability, and unable to provide instantaneous feedback to operators for adjustments to operational parameters aimed at mitigating losses.

It is possible to monitor grain loss in real time and generate corresponding signals using modern sensor technology. Subsequently, these signals can be identified and quantified using microcontroller technology to obtain precise grain loss data. This approach significantly increases the efficiency of loss measurement while enhancing the real-time monitoring capability. As a result, it provides effective guidance for operators to fine-tune the settings of their harvesters, facilitating a decrease in harvest losses [4].

Many developed countries began studying grain loss detection sensors for combine harvesters in the 1960s. The goal was to accurately measure grain loss during the harvest process in real time and to use this information to guide the adjustment of the harvester's operating parameters [5].

Currently, many advanced foreign combine harvesters are equipped with grain loss monitoring sensors. For example, John Deere's JD9660STS, Case's 2366IH, and CLASS's TRION740 are all models that include this technology. These sensors monitor grain loss during the harvesting process, helping the operator to understand and promptly respond to any grain loss that occurs after threshing and separating [6,7].

In the 1970s, foreign scholars J.R. Botterill and J.C.F. Girodat developed a grain loss monitoring system [8]. This system monitored the grain loss of the harvester over time by using a grain loss monitoring sensor installed at the rear of the machine. Building on the research by J.R. Botterill and J.C.F. Girodat in 1976, Shaver, J. Lyle, and others incorporated the walking speed of the combine harvester into the monitoring system [9]. This enabled the system to display grain loss per unit area in real time and to be adaptable to various crops. In 1977, W.P. Strelioff, C. Liu, and others proposed using capacitive microphones to capture the sound signal produced when the mixture collides with the metal tube. The grain loss during cleaning was then determined by amplifying and filtering this sound signal [10]. In 2016, Btcheller and colleagues designed a particle collision sensor that uses the principle of acoustic electricity. This sensor distinguishes different materials based on the sound signals produced when materials collide with it, which are collected by a microphone [11].

Domestic scholars have been researching real-time measurement devices for grain loss rates, utilizing the piezoelectric principle. The grain loss data obtained from harvesters is used as feedback to enable real-time control of the overall system.

In 2008, a team led by Mao proposed the development of a piezoelectric crystal vector sensor array [12], which facilitates multi-point real-time monitoring of various parameters. The following year, Zhang Tian and colleagues [13] employed machine vision technology to capture images at the outlet of the debris removal section, allowing for an accurate count of lost grains. In 2010, Xu Jiaojiao [14] created a mathematical model to assess the loss associated with material carried away through the grass outlet and the amount of grain separation at the end of the threshing drum, identifying the most effective location for positioning the loss sensor. That same year [15], Zhou Liming and his team adopted polyvinylidene chloride (PVDF) piezoelectric film as the sensitive element in their sensors. They engineered an array PVDF sensor along with a corresponding signal conditioning circuit, which was instrumental in capturing the spatial distribution of grain loss.

In 2011 [16], Li Yaoming and colleagues developed a real-time monitoring system for grain loss. To mitigate the impact of vibrational disturbances from the combine harvester, they engineered a sophisticated double-layer vibration isolation structure. Building on this study, in 2018 [17], Sun Ying introduced a novel particle collision sensor featuring a double-layer cross structure built with PVDF piezoelectric film. This innovative sensor could not only distinguish between particles colliding simultaneously but also enhance saturation capacity. Moreover, it was capable of extracting collision position information by utilizing the synchronized response of the dual-layer sensing elements.

There are still some deficiencies in the practical application of wheat harvester grain loss monitoring technology, and it is necessary to investigate further [18]. In the present research, aiming at the problem of large cleaning losses in wheat harvesters, a monitoring device for grain cleaning losses in wheat combine harvesters is developed. This research

attempts to solve the problem of lagging measurement results of artificial loss by monitoring the cleaning loss in the process of wheat harvesting in real time, and to better guide the harvester driver to adjust the parameters to reduce the loss and achieve the purpose of reducing the loss of harvest.

2. Materials and Methods

2.1. The Structure

The mechanized operation process of wheat combine harvesters is generally divided into harvesting, threshing, separation, cleaning, grain collection, and other links. The corresponding harvest losses are header loss, threshing loss, entrainment loss, cleaning loss, and grain leakage loss, among which cleaning grain loss accounts for a large proportion [19]. In the traditional wheat harvesting operation, the harvester drivers can only adjust the harvester operation parameters by driving experience to reduce cleaning losses and other types of losses, and there is no specific data for accurate guidance. A monitoring device for wheat combine harvester grain cleaning loss described herein is installed on the harvester to monitor the cleaning loss in real time and guide the driver to decrease the loss of harvest. It includes a two-way array piezoelectric sensor, a material collision signal processing system, and a human–computer interaction system. The structure of the wheat combine harvester cleaning loss monitoring device is shown in Figure 1.

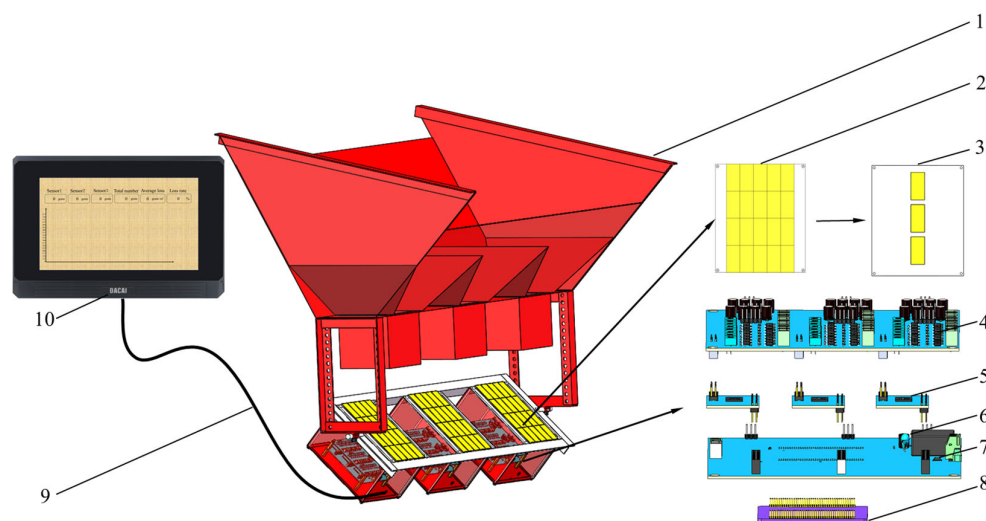


Figure 1. Structure composition diagram of the monitoring device: 1. collection hopper, 2. bidirectional array piezoelectric sensor, 3. vibration signal compensation device, 4. signal amplification module, 5. AD7606 analog-to-digital conversion module, 6. power supply circuit, 7. CAN communication module, 8. TMS320F28335 core processor module, 9. CAN bus, and 10. aerial screen.

2.2. Working Mechanism

During the normal harvest operation of the wheat combine, the ejection of the cleaning device falls on the screen plate [20], the long stalk is sent out of the machine through the reciprocating movement of the screen plate, and the kernel and part of the short stalk fall into the material concentration box through the outlet for free fall. The main function of the collection hopper is to change the angle of the material impact sensor to keep the collision angle consistent.

Figure 2 shows a schematic representation of the cleaning loss monitoring device. When the material collides with the bidirectional array piezoelectric sensor based on piezoelectric ceramics, the piezoelectric ceramics produce a piezoelectric effect output electrical signal, and the piezoelectric ceramics of the vibration signal compensation device on the back of the sensor can be subjected to mechanical vibration. The electrical signal generated by material collision and the electrical signal generated by vibration are amplified

by the signal amplifier device simultaneously, and the mode converter comprising an AD7606 chip is collected and converted into the digital signal composed of binary numbers. Then, it is sent to the TMS320F28335 chip through SPI serial communication to compensate for the collision signal data and identify and count the grain to acquire the cleaning loss data. Then it is sent to the built-in man-machine interaction system of the serial screen through a CAN communication bus for data display and calculation of the cleaning loss rate.

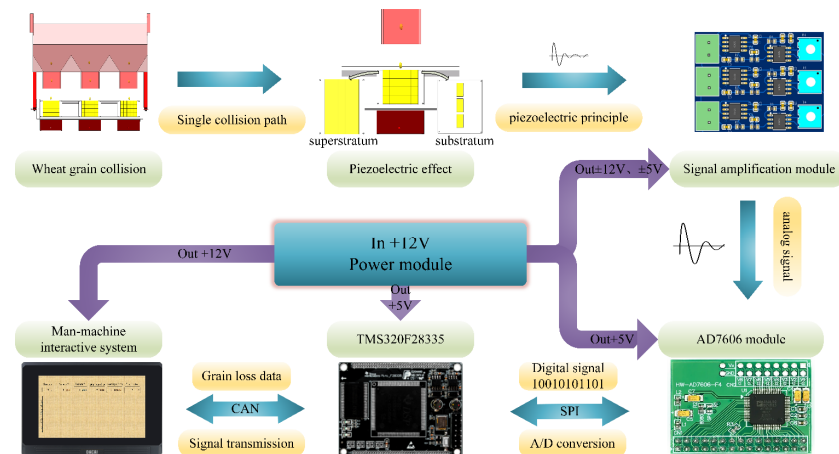


Figure 2. The working principle diagram of the monitoring device.

2.3. Hardware Circuit Design

The design of the hardware circuit is an important part of the wheat combine harvester grain cleaning loss monitoring system. It mainly includes the selection and design of the grain collision sensor, the design of the signal processing system, and the selection of human-computer interaction system hardware.

First, factors such as sensitivity, stability, and reliability need to be considered when selecting and designing grain collision sensors. The sensor should be able to accurately detect the collision between the grain and the sensor and convert it into an electrical signal output. Meanwhile, the sensor should also have good anti-interference ability and be able to work stably in a complex working environment. Second, the design of the signal processing system needs to be properly processed and analyzed according to the electrical signals output by the sensor. This includes signal amplification, sampling, and analog-to-digital conversion steps. Through the material collision signal processing system, the weak electrical signal output by the sensor is converted into lost-grain data and sent to the human-computer interaction system. Finally, the hardware carrier of the human-computer interaction system, the serial port screen, is selected. According to the development environment, design resources, whether they support the secondary development of programming, and whether they meet the design requirements of the human-computer interaction system can be judged.

According to the monitoring requirements of the wheat combine harvester cleaning loss monitoring device, the hardware structure of the designed monitoring device is shown in Figure 3. It is mainly composed of a bidirectional array piezoelectric sensor, vibration signal compensation device, signal amplification module, AD7606 analog-to-digital conversion module, TMS320F28335 core processor module, CAN bus communication module, and serial port screen.

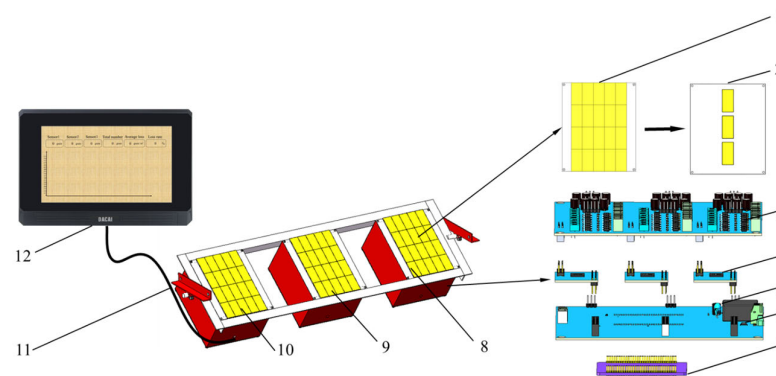


Figure 3. Hardware structure of the cleaning loss monitoring device: 1. a bidirectional array piezoelectric sensor, 2. a vibration signal compensation device, 3. signal amplification module, 4. AD7606 analog-to-digital conversion module, 5. power supply circuit, 6. CAN communication module, 7. TMS320F28335 core processor module, 8. bidirectional array piezoelectric sensor-1, 9. bidirectional array piezoelectric sensor-2, 10. bidirectional array piezoelectric sensor-3, 11. CAN bus, and 12. serial screen.

2.3.1. Design of a Bidirectional Array Piezoelectric Sensor

Currently, the most used and studied sensors in the research field of loss monitoring are based on machine vision and piezoelectric principles.

The sensor based on machine vision requires the installation of a camera in the monitoring position, the collection of thrown object photographs in real time through the camera [21], followed by image processing and identification of wheat grains in the photographs. When the harvester is working in the field, a large amount of dust is produced. Due to the dusty working environment, the camera cannot collect clear pictures, and even the dust is attached to the lens so that it cannot work normally to collect photographs, resulting in a loss monitoring device based on the principle of machine vision being unable to achieve better results. The sensor, based on the piezoelectric principle, collides with the material. The piezoelectric material can produce a piezoelectric effect to output electrical signals with different amplitudes and waveforms. Based on this, the wheat grain collision signal is identified.

The piezoelectric sensor, which operates without the need for external power and generates electrical signals through material collisions [22], has emerged as the predominant research focus in grain loss sensors due to its simple structure, reliable operation, and lightweight design [23]. Therefore, a piezoelectric-based sensor was chosen for investigation. Piezoelectric ceramics and polyvinylidene fluoride are the most widely used piezoelectric materials. However, in comparison, piezoelectric ceramics have strong piezoelectricity and a high dielectric constant [24]. Piezoelectric ceramics were used as piezoelectric materials to make the grain collision sensor described herein. The parameters of piezoelectric ceramics are listed in Table 1.

Table 1. Performance parameters of piezoelectric ceramics.

Performance Index	Parameter
Relative dielectric constant	3400
Planar electromechanical coupling factor	0.62
Young's modulus	$56 \times 10^9 \text{ N/m}^2$
Poisson ratio	0.36
Density	$7.6 \times 10^3 \text{ kg/m}^3$

As illustrated in Figure 4, this article uses a 0.2 mm-thick bronze sheet as the sensitive plate and a corresponding 0.2 mm-thick piezoelectric ceramic as the piezoelectric material to construct an individual piezoelectric sensor unit. Upon generation of a piezoelectric effect, the electrical signal is transmitted through the two wires that are soldered to both the bronze sheet and the piezoelectric ceramic.

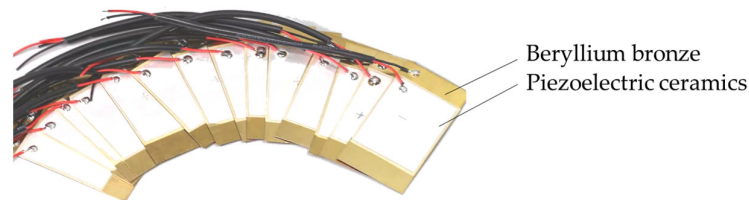


Figure 4. Piezoelectric sensor unit.

To validate the practicality of a piezoelectric sensor monomer as a grain collision detector, experiments were conducted where wheat grains, wheat stalks, and wheat glume shells were dropped from the same heights to collide with the sensor. The resulting output electrical signals are illustrated in Figure 5 [25]. The output signals of collision-sensitive units of wheat grain, wheat stem, and wheat glume were analyzed. Piezoelectric sensors can generate electrical signals when they are impacted by external forces. This observation is consistent with the behavior of piezoelectric ceramics, which generate a piezoelectric effect in response to external forces and produce an electrical signal. The peak values of the electrical signal output when different materials collide with the sensitive unit at the same height are then compared. It is found that the glume collision results in the smallest peak value, followed by the wheat grain collision, with the wheat stem collision producing the largest peak value; the obvious waveforms generated by the collision of each material appear, with a clear difference in the peak range of each waveform. Therefore, the piezoelectric sensor unit developed in the present research, made of piezoelectric ceramics and beryllium bronze, is used as a material for making grain-collision sensors.

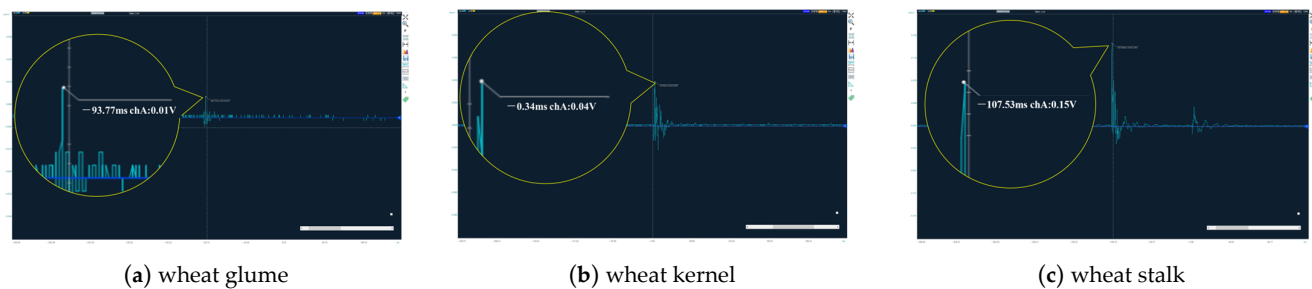


Figure 5. The peak value of the collision signal of different materials at the same height.

Figure 6 shows the bidirectional array structure [26–29]. In this article, piezoelectric sensor monomers are arranged horizontally and vertically to create a larger sensor area, thereby extending the monitoring range. Each sensor unit in the bidirectional array piezoelectric sensor is paired with its own processing module dedicated to monitoring a specific area, enhancing the accuracy of signal processing. Furthermore, when multiple grains collide simultaneously with the bidirectional array piezoelectric sensor, each unit can independently transmit a collision signal without interference. The bidirectional array piezoelectric sensor enhances the monitoring capacity by enabling simultaneous detection of multiple grain collisions, thereby increasing the overall sensor accuracy.

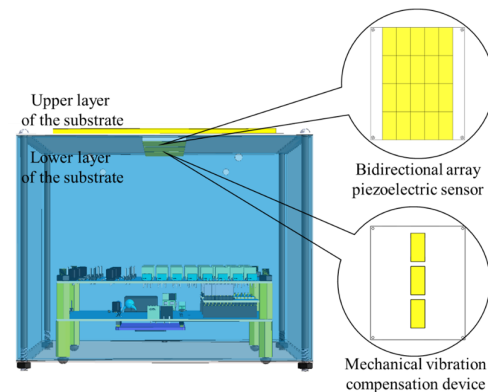


Figure 6. Structural design of a piezoelectric sensor.

Meanwhile, the monitoring device for wheat harvester grain cleaning loss needs to be installed at the tail of the harvester to monitor the grain cleaning loss. The piezoelectric sensor used in this study is affected by vibration, so it is necessary to reduce the influence of mechanical vibration on the piezoelectric sensor. To address this issue, a method of signal compensation was proposed [30]. The method aims to reduce the influence of mechanical vibration on the bidirectional array piezoelectric sensor, and the vibration signal compensation device is shown in Figure 6.

The working principle of the signal compensation device involves collecting mechanical vibration data in real time. This is performed by a plurality of piezoelectric sensor units arranged on the back of the bidirectional array sensor, which outputs an electrical signal. This generated electrical signal is then fed back to the front piezoelectric ceramic. The device performs signal compensation to diminish the impact of mechanical vibration on the output electrical signal of the front sensor. As a result, a material collision signal unaffected by mechanical vibration is obtained for subsequent signal processing.

2.3.2. Design of a Material Collision Signal Processing System

The material collision signal processing system designed in the present research comprises a signal amplification module, an analog-to-digital conversion module, a core processor module, a CAN communication module, and a power supply module. It primarily performs the amplification, sampling, analog-to-digital conversion, grain identification, counting, and CAN communication of the sensor output signal.

(1) Signal amplification module

Piezoelectric ceramics become polarized due to the relative displacement of their internal positive and negative charge centers, which occurs when the material deforms. This results in the appearance of bound charges with opposite signs on the surfaces of both ends of the material, generating an electrical signal. When the piezoelectric ceramic is fixed, its electrical signal is significantly reduced compared to when it is in a free state. Additionally, piezoelectric ceramics demonstrate a high output impedance; their internal resistance is extremely high, leading to a small output electrical signal. Therefore, to bring the output electrical signal of the sensor to a suitable level for subsequent measurement and calculation, a signal amplification circuit is required [31].

This signal-amplifying circuit uses the OPA656 chip to construct a first-stage amplifier circuit and the TL072 chip to form a second-stage amplifier. As depicted in Figure 7, both chips are powered by a positive and negative dual power supply. This configuration enhances the dynamic range of the operational amplifier, diminishes circuit noise, and augments the stability and reliability of the amplifier circuit. To modulate the gain (A) of the amplifier circuit, we have incorporated a potentiometer $R1$ into the design. Adjusting its resistance allows for precise control over the amplification factor, as shown in Formula (1).

By adjusting the resistance value of $R1$, the grain collision signal can be amplified by 1 to 100 times.

$$A = \frac{R1}{R4} + 1 \quad (1)$$

where A represents the amplification gain of the signal, $R1$ represents the resistance value of the signal amplifier circuit resistor 1, and $R4$ represents the resistance of the signal amplifier circuit resistor 4.

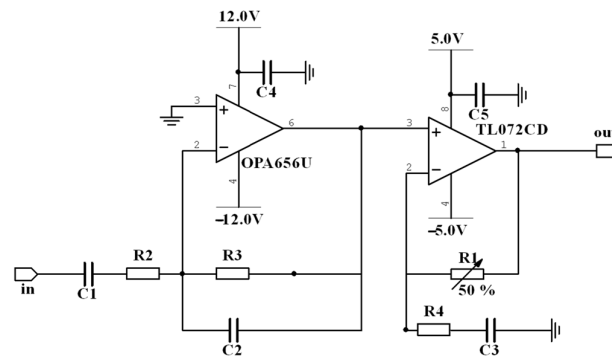


Figure 7. Signal amplifying circuit.

(2) Core processor module

The core processor is pivotal to the monitoring system, serving as the backbone responsible for its operational efficiency and control mechanisms. When selecting a core processor, it is essential to weigh various factors, such as the specific application requirements, computational capabilities, precision, and suitability of the development environment. Among the array of common microcontrollers are the 51 series, STM32, digital signal processors (DSP), and field-programmable gate arrays (FPGA). After a comprehensive evaluation of these parameters, Texas Instruments' 32-bit floating-point processor, the TMS320F28335 chip from the TMS320C28x family, has been chosen as the principal processor. As depicted in Figure 8 below, the most compact system board engineered with the TMS320F28335 at its core was presented (also referred to as a DSP28335).

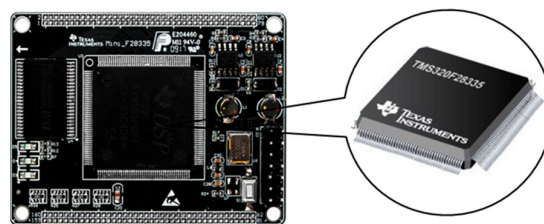


Figure 8. TMS320F28335 core processor module.

The DSP28335 boasts a triad of notable attributes: superior precision, cost-effectiveness, and minimal power consumption. In the realm of processing prowess, the TMS320F28335 is capable of executing 150 million instructions per second. Regarding peripheral resources, it offers options including versatile GPIO interfaces, SPI interfaces, and CAN communication interfaces. As for computational accuracy, the chip encompasses a full-fledged single-precision (32-bit) IEEE754-compliant floating-point unit (FPU), which facilitates both single-precision and double-precision floating-point operations.

(3) Analog-to-digital converter

The analog output voltage signal derived from the piezoelectric ceramics used in this investigation must be converted to a digital format, a process that entails sampling, holding, quantizing, and encoding via a mode converter [32]. While the on-chip ADC capabilities of the DSP28335 are adequate for general applications and can fulfill most measurement

needs, they are inadequate for the specific design criteria of this research. Additionally, the inherent ADC suffers from a subpar conversion rate, inferior accuracy, and a limited channel count. For these reasons, an external ADC has been selected for use in this study. The expanded ADC is centered around the AD7606 chip, manufactured by Analog Devices. This high-resolution 16-bit analog-to-digital converter provides a single device with eight simultaneous sampling channels, a maximum sampling rate of 200 kSps, and an input voltage range of either ± 10 V or ± 5 V. The AD7606 analog-to-digital conversion module selected in this study is shown in Figure 9.

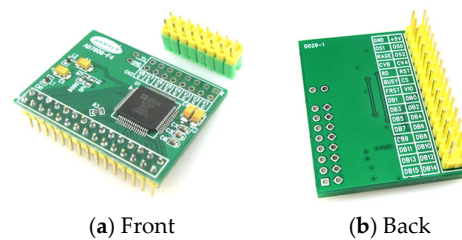


Figure 9. AD7606 modulus physical figure.

According to the design requirements of this study, each bidirectional array piezo-electric sensor needs to expand three AD7606 analog-to-digital conversion modules. The AD7606 analog-to-digital converter has two communication modes, namely, serial communication mode and parallel communication mode, as shown in Figure 10.

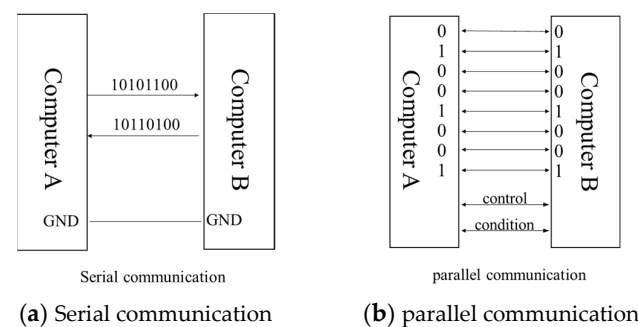


Figure 10. AD7606 module data transmission mode.

The corresponding communication interface mode can be selected by setting the high- and low-level combination of PAR/SER/BYTE SEL pins and DB15 pins of AD7606, as shown in Table 2.

Table 2. Interface mode selection table.

PAR/SER/BYTE SEL Pins	DB15 Pins	Interface Mode
0	0	Parallel interface
1	0	Serial interface
1	1	Parallel byte interface

The SPI communication protocol is favored for its simplicity, ease of implementation, and clarity, as well as its support for full-duplex communication and decreased demand for transmission lines [33]. This minimizes the use of the chip's GPIO ports and simplifies PCB wiring complexity. Consequently, this research selects the SPI mode for data exchange between the AD7606 module and the DSP28335. To specify, the PAR/SER/BYTE SEL pin is set high, while the DB15 pin is set low to engage the SPI serial interface mode. The connection architecture between the DSP28335 core processor and the AD7606 analog-to-digital converter is illustrated in Figure 11. The AD7606 converter designated for reading is chosen through the CS chip select signal managed by the DSP28335.

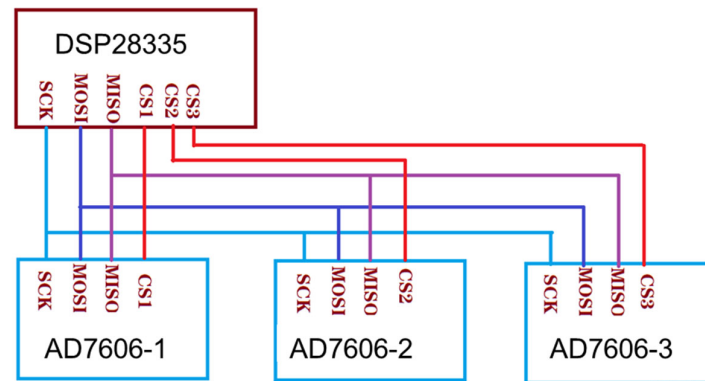


Figure 11. SPI communication wiring diagram of DSP28335 and AD7606.

The configuration of the AD7606 analog-to-digital converter is simplified by the absence of internal registers. The setup of the range and oversampling parameters is facilitated through an external GPIO interface. Additionally, the sampling rate is dictated by the PWM (pulse width modulation) signal frequency that is provided by the DSP28335. Details of the AD7606 configuration pins and their functions are shown in Table 3.

Table 3. AD7606 configuration pins and functions.

AD766 Pins	TMS320F28335 Pins	Function
OS1, OS2, and OS3	GPIO0, GPIO1, and GPIO2	Set the oversampling rate
RANGE	GPIO3	Set the sampling voltage range
CVA and CVB	GPIO10	Control begins to convert
RST	GPIO11	Reset
RD	GPIO56	Serial clock input
BUSY	GPIO12	Busy conversion
CS (CS1, CS2, and CS3)	GPIO57, GPIO16, and GPIO17	Chip selection signal line
DB7	GPIO55	Data output pin
DB15	GND	Communication mode selection pins

(4) Communication method

The communication interface circuit serves as an essential conduit for information exchange between the collision signal processing system and the human–computer interaction system, playing an indispensable role in modern communication. Presently, the prevailing communication protocols encompass RS-232, RS-485, and CAN communication. The CAN communication bus is chosen to facilitate efficient information transfer between the material collision signal processing system and the human–computer interaction system. This selection is predicated upon a thorough evaluation of attributes such as adaptability in multi-node network configuration, real-time transmission capabilities, network architectural diversity, and system dependability, as delineated in Table 4.

Table 4. Comparison of communication modes.

	RS-232	RS-485	CAN
Communication distance	30 m (max)	3 km (max)	10 km (max)
transmission rate	20 Kbps	10 Mbps (max)	1 Mbps (max)
Network structure	Single-master	Single-master	Multi-master
Node failure	Influence the whole	Influence the whole	Does not influence the whole

The DSP28335 integrates an eCAN module that adheres to the 2.0 B specification of the CAN communication standard. As a result, the principal focus in designing the CAN communication circuit is on the CAN transceiver electronics. This document delineates

a CAN bus communication interface circuit designed with the TJA1040 component at its core, as shown in Figure 12.

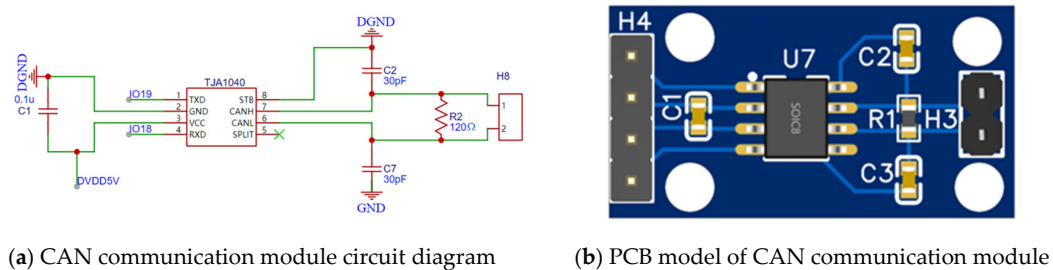


Figure 12. CAN communication module.

The architecture diagram of the CAN bus communication framework is shown in Figure 13. The TMS320F28335 core board connects the network node with the CAN bus network through the CAN communication module. There are four nodes in the CAN bus transmission network, three TMS320F28335 send loss data, and one serial port receives loss data.

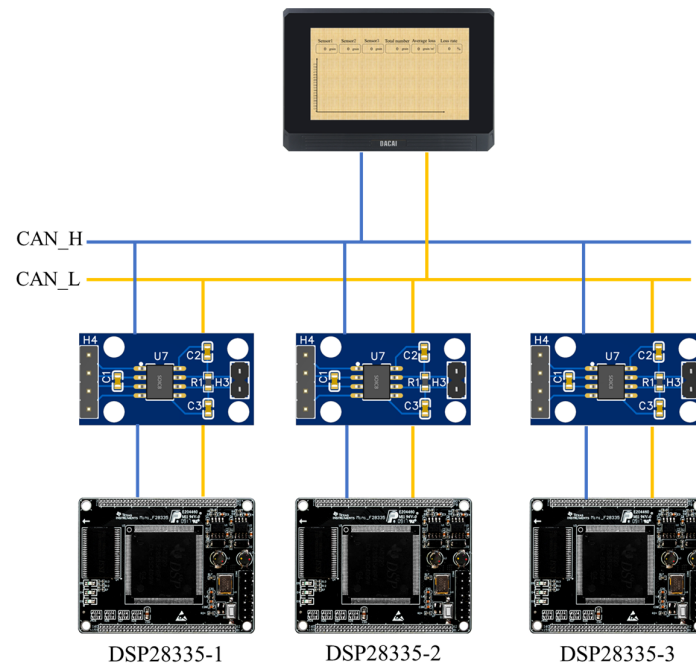


Figure 13. CAN bus communication network.

2.3.3. Select the Display Terminal

For man–machine interaction systems, hardware equipment serves as an essential carrier. In this paper, a serial display was used as the hardware component of the man–machine interaction system, which facilitates bidirectional information exchange between the single-chip computer and the system itself, as well as between the system and the drivers in a pairwise manner. By comprehensively evaluating the performance and features of serial display products from these and other companies and considering the specific design criteria for the human–computer interaction system discussed in this research, the serial screen produced by Guangzhou Dacai Optoelectronics Technology Co., Ltd. is selected, as shown in Figure 14. The technical specifications of this display model are summarized in Table 5.



Figure 14. Serial port screen physical diagram.

Table 5. Performance parameters of the serial port screen.

Item	The Parameter of Product
Power supply	9~36 V DC voltage
Communication interface	RS-485, CAN, and Ethernet
Development mode	LUA secondary development
Audio format	MP3
Memory space	1 GB of storage space

2.3.4. The Design of a Power Supply Circuit

The devices requiring power within the cleaning loss monitoring apparatus of the wheat combine harvester consist of the operational amplifier chips OPA656 and TL072, which are integral to the signal amplification circuitry; the minimal system board, with the DSP28335 processor at its core; the AD7606-centric analog-to-digital converter; the CAN bus communication interface predicated on the TJA1040 chip; and the serial port display. The requisite power supply voltages for these components are listed in Table 6.

Table 6. Power supply voltage requirements of electrical devices.

Electrical Devices	Power Supply Demand
OPA656 chip	± 5 V
TL072 chip	± 12 V
DSP28335 core processor module	+5 V
AD7606 module	+5 V
TJA1040 chip	+5 V
Serial display screen	+9 V~+36 V

The design of the overall power supply for the circuit is predicated upon the specific power requirements of each consuming module or component, as shown in Figure 15. This figure elucidates the topological schematic of the power supply arrangement for the monitoring apparatus's electrical circuitry. The digital interface voltage for the AD7606 integrated circuit mandates a 3.3 V input. The processor core of the DSP28335 stipulates a 1.9 V supply, whereas the voltage for the IO ports necessitates a 3.3 V provision. Notwithstanding, both the AD7606 analog-to-digital converter and the DSP28335-based system board can be adequately powered by a nominal 5 V input source owing to the presence of corresponding power conversion circuits embedded within the module.

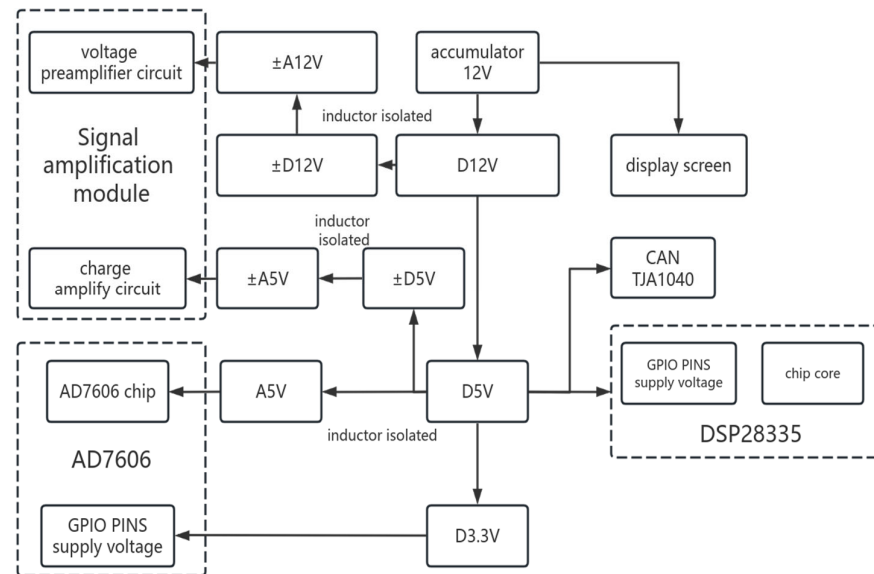


Figure 15. Power supply topology diagram of a power supply circuit.

- (1) A circuit for converting +12 V input to +5 V output

According to the power supply requirements of each module, many modules require a +5 V power supply. The URBYMD-10WR3 power module is selected to design the +12 V conversion +5 V circuit, as shown in Figure 16.

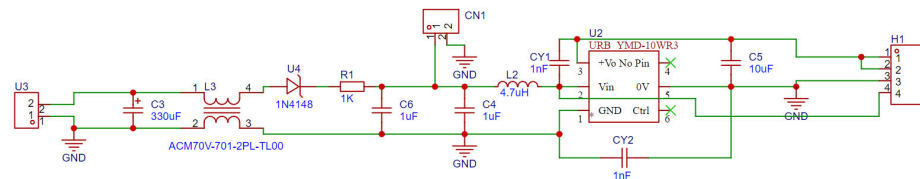


Figure 16. + 12 V conversion + 5 V circuit diagram.

- (2) Negative voltage-generating circuit

Since both the OPA656A and TL072 operational amplifiers require a negative voltage power supply, the SGM3209 voltage converter is chosen to design a negative voltage generation circuit. Figure 17 shows the circuit design for converting +5 V to -5 V, and Figure 18 presents the circuit design for converting +12 V to -12 V.

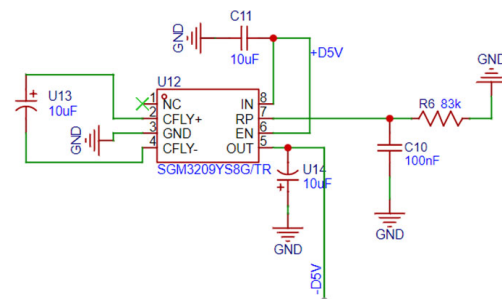


Figure 17. + 5 V conversion–5 V circuit diagram.

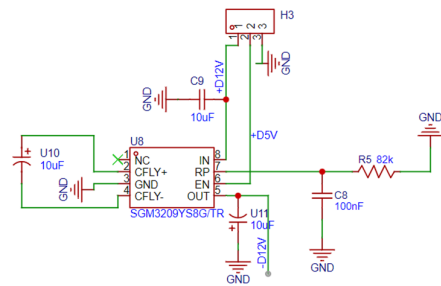


Figure 18. +12 V conversion–12 V circuit diagram.

2.4. Software Function Design

First, the AD7606 driver is designed to collect multi-channel collision signals in real-time. Second, the SPI communication program transmits the collected data to the TMS320F28335 core processor in binary form. Then, the vibration signal compensation program reduces the impact of mechanical vibrations on the piezoelectric sensor's output signal. The grain recognition and counting program identifies and counts the grain collision signals. Finally, the loss data are transmitted to the CAN communication network using the CAN communication program. The overall design of the human–computer interaction system is executed using serial screen development software (Figure 19). The overall software design flow chart is shown in Figure 19. This includes the page design of the login screen, the basic parameter interface, and the loss data display interface, as well as the program design for receiving loss data from the CAN communication network, ensuring that the loss data are displayed at the corresponding interface positions.

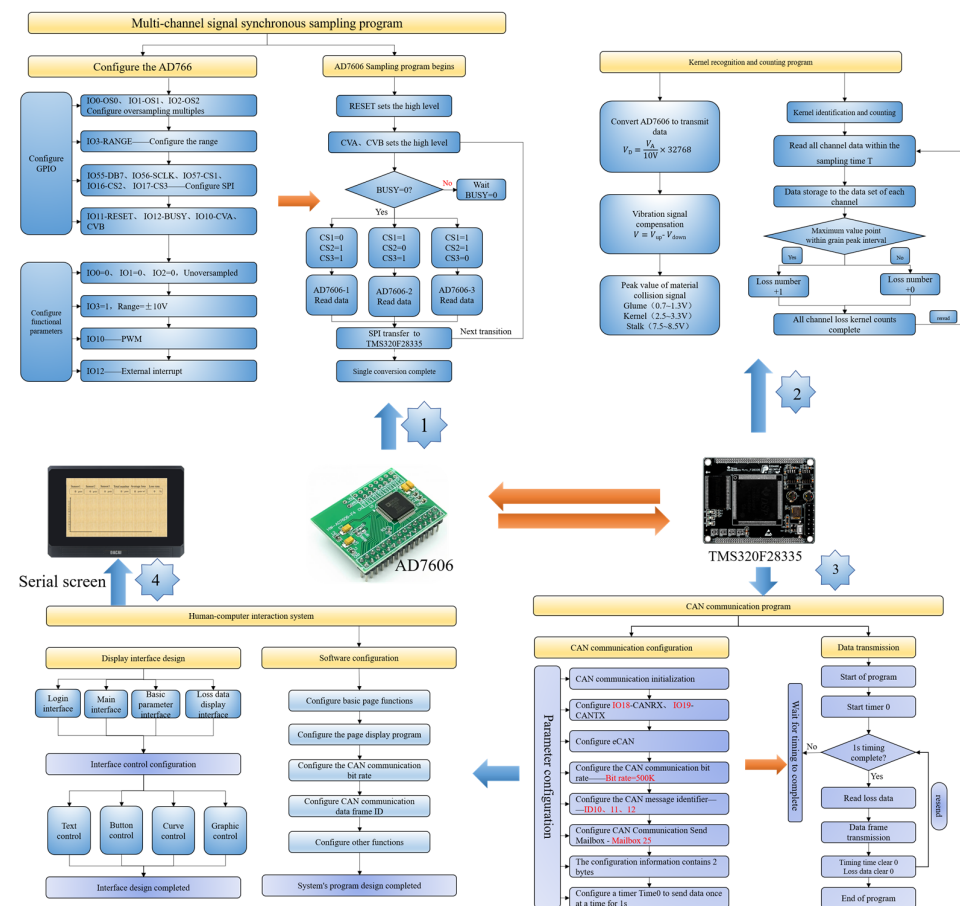


Figure 19. Software overall design flow chart.

2.4.1. Electrical Signal Data Acquisition Program

In the context of this research, the AD7606 analog-to-digital converter employs the Serial Peripheral Interface (SPI) mode for data exchange with the DSP28335 microprocessor. Within the communication framework, the DSP28335 is designated as the master device, tasked with receiving data from the AD7606. Conversely, the AD7606 is configured as a slave device, responsible for transmitting data. Given that the AD7606 lacks internal register capabilities, the DSP28335 orchestrates the initiation and cessation of the AD7606's operations by asserting high- and low-level signals through its General-Purpose Input/Output (GPIO) ports. Figure 20 delineates the timing diagram associated with the AD7606's acquisition of single-channel sample values, elucidating the precise temporal sequence and interaction pattern among the critical signals involved in the SPI communication process. This meticulous synchronization ensures the accurate transfer and processing of data. The implementation of the data acquisition program, predicated on SPI communication, achieves efficient data interchange between the DSP28335 and AD7606, thereby laying a robust groundwork for subsequent data processing and analytical pursuits.

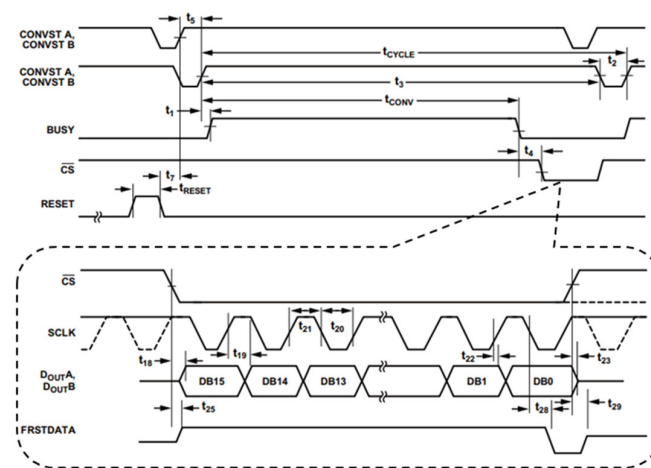


Figure 20. AD7606 serial data acquisition timing diagram.

The sequence diagram in Figure 19 illustrates the analog-to-digital conversion process of the AD7606. Initially, to initiate the acquisition, a high-level RESET signal is required to reset the device, where a high level is effective for the reset. Subsequently, the CVA and CVB are pulled low for a minimum of 25 ns before being brought high (with the rising edge of the start signal being the effective trigger). Once this is performed, the AD7606 commences the conversion process, during which the BUSY signal line remains high. Upon completion of the conversion, the BUSY signal line transitions to a low level. It is only after the conversion is finished that the data can be read, which necessitates pulling the CS chip selection signal line low. Finally, after the data has been read, the CS chip selection signal line is returned to a high level. This meticulous sequence ensures accurate and efficient data acquisition by the AD7606.

With reference to the timing diagram for the serial read of a single channel from the AD7606 chip's data manual, this study has formulated an acquisition flow chart that involves the utilization of three AD7606 chips. In accordance with the SPI communication protocol, the selection of a particular AD7606 chip is accomplished by setting its CS (Chip Select) pin to a low logic level. In the present study, the CS1, CS2, and CS3 pins are activated individually to select each AD7606 chip and execute the reading of data from their aggregate of 24 conversion channels. The acquired data are subsequently relayed to the DSP28335 for further processing via the SPI communication interface. This guarantees precise control over the data acquisition from the three AD7606 chips, ensuring efficient data retrieval and providing dependable inputs for the DSP28335's data processing operations. The flow chart of the multi-channel signal synchronous acquisition program is shown in Figure 21.

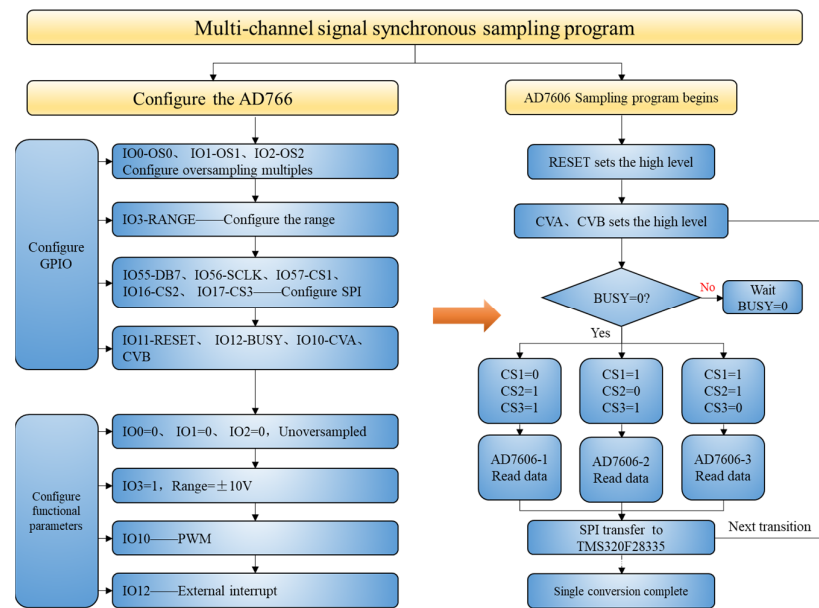


Figure 21. Multi-channel signal synchronous sampling procedure flow chart.

2.4.2. Data Conversion and Signal Compensation Program

The process of signal conversion entails the translation of binary data obtained from the AD7606 into decimal representations of voltage. The AD7606, an analog-to-digital converter with 16-bit precision, has its analog input range set within this study to ± 10 V. This results in a total input span of 20 V, which is finely divided into 65,536 distinct segments. Before the conversion commences, it is imperative to discern the polarity of the sampled voltage. This key decision hinges on the examination of the most significant bit in the binary data: a value of '0' signifies a positive voltage, while a value of '1' denotes a negative voltage. Once the polarity is determined, the top bit is masked, and the remaining bits are processed using Formula (2), which converts them into a decimal voltage value. The final step involves applying the appropriate polarity sign to the converted value, based on the initial determination. Through this procedure, the raw binary data captured by the AD7606 is converted into its corresponding voltage measurement. The vibration signal compensation device is shown in Figure 22, and the pure grain collision signal is obtained.

$$V_D = \frac{V_A}{10V} \times 32,768 \quad (2)$$

In Formula (2), V_D represents the voltage value, and V_A represents the binary number of the sampled value.

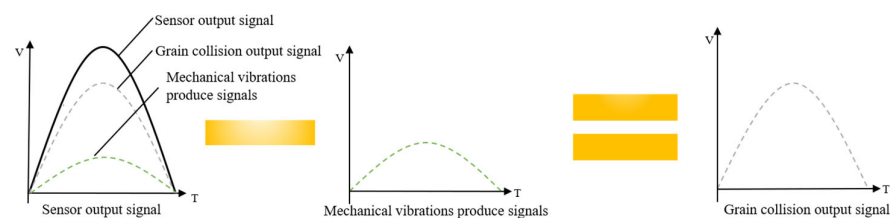


Figure 22. Bidirectional array piezoelectric sensor output signal composition.

A bidirectional array sensor integrates two primary electrical signal components within its output: one is the electrical response elicited by material impact with the sensor, and the other arises from mechanical vibration. Among these signals, those generated by mechanical vibration often manifest as random and irregular noise. Such noise not only fails to contribute positively to the effective capture of sensor data but also impedes subsequent

signal analysis. To extract and analyze the meaningful electrical signals produced by material collision, it is imperative to employ appropriate signal processing techniques that eliminate or significantly reduce the electrical noise associated with mechanical vibration.

To improve the detection accuracy and stability of the bidirectional array piezoelectric sensor, a signal compensation method is employed in this study. Specifically, by installing a specialized signal compensation device on the reverse side of the bidirectional array piezoelectric sensor, this apparatus is tasked with continuously monitoring and gathering electrical signals induced by mechanical vibrations. These collected data are subsequently fed back into the sensor's output signal at the front end, nullifying the mechanical vibration components present in the original signal. This compensatory mechanism not only improves the precision of the data but also yields a cleaner and more interpretable signal input for subsequent signal processing and analysis. The voltage value for each collision signal of the acquired material is computed using Formula (3).

$$V = V_{up} - V_{down} \quad (3)$$

In Formula (3), V represents the actual material collision voltage value, V_{up} represents the voltage value generated by the upper bidirectional array piezoelectric sensor, and V_{down} represents the voltage value generated by the lower vibration signal compensation device.

2.4.3. Wheat Grain Identification and Counting Program

In this study, the criteria for determining whether a collision signal is generated by the collision of wheat grains primarily involve two aspects. First, a time recognition interval is established based on the duration of the wheat grain collision signal. This interval is set according to the time between the onset and termination of the collision signal from the wheat grain. Subsequently, multiple voltage value readings are obtained within this time recognition interval. These voltage values, collected at different times, are compiled into an array. The voltage meter at each sampling point, denoted as X_n , where n is a positive integer, is read. The sum of the voltages of all sampling points within the sampling point is calculated and referred to as the characteristic sum, M_f . Subsequently, the characteristic set M_f of the sampling points within the time window can be represented by Formula (4).

$$M_f = \{X_1, X_2, X_3, X_4, X_5, \dots X_n\} \quad (4)$$

By analyzing whether the array contains a maximum value and whether this peak value falls within the characteristic peak interval of the wheat grain collision, it is determined whether a grain signal is present within the time recognition interval. The schematic diagram of wheat kernel recognition and counting is shown in Figure 23.

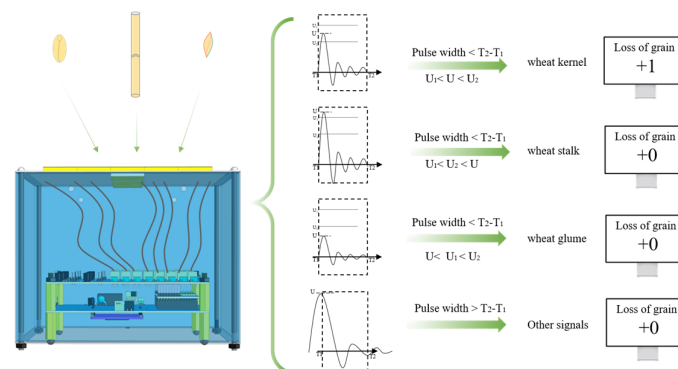


Figure 23. The schematic diagram of wheat grain recognition and counting.

In the study, it is noted that the electrical signal peaks generated by the collision of wheat grains, glumes (husks), and stems with the sensor differ significantly. These differences can be accentuated through signal amplification, enabling the identification

of grains and other materials based on distinct collision signal peaks. As can be seen from Figure 24, the collision signal interval of wheat kernel, glume, and stalk is obvious. However, due to the small mass of wheat glume, kernel, and stalk, the peak value of the collision signal is not very different at different heights. The peak value of the glume shell collision signal was mostly between 0.7 and 1.3 V, the grain collision signal was mostly between 2.5 and 3.3 V, and the stalk collision signal was mostly between 7.5 and 8.5 V. The flow chart of the kernel collision identification and counting program is shown in Figure 25.

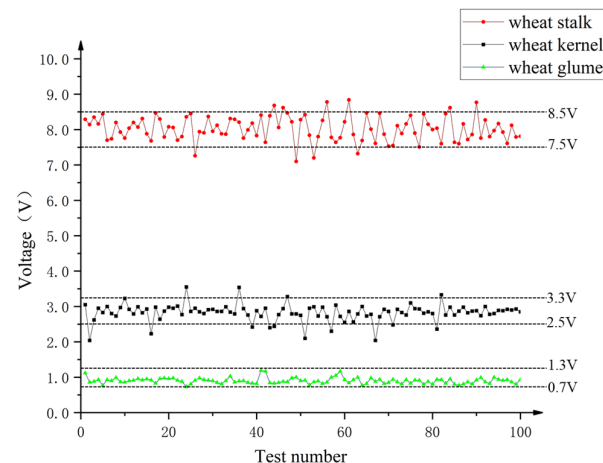


Figure 24. Wheat glume, wheat grain, and wheat stem collision voltage signal peak.

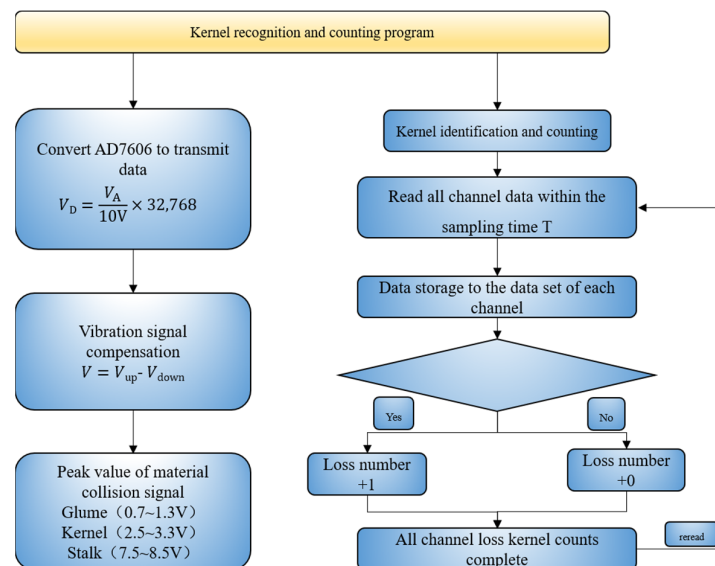


Figure 25. Collision kernel identification and counting program flow chart.

2.4.4. CAN Total Selection Communication Program

The CAN bus uses a differential signal for data transmission, employing the transmission lines CAN_L and CAN_H [34,35]. The potential difference between these lines determines whether the transmitted data represents a 1 or a 0. Data on the CAN bus can be conveyed through structured data frames, which delineate the primary structure of a data frame. The arbitration field within the data frame encompasses an identifier bit, which serves as a functional address. The CAN receiver uses this identifier to filter incoming data frames. Successful reception of a data frame is contingent upon a match between the identifier bits, that is, the frame IDs must be identical. Comprising 0 to 8 bytes, the data field of the data frame contains the information intended for transmission by the data

frame. The flow chart of the CAN communication configuration and data sending program is shown in Figure 26.

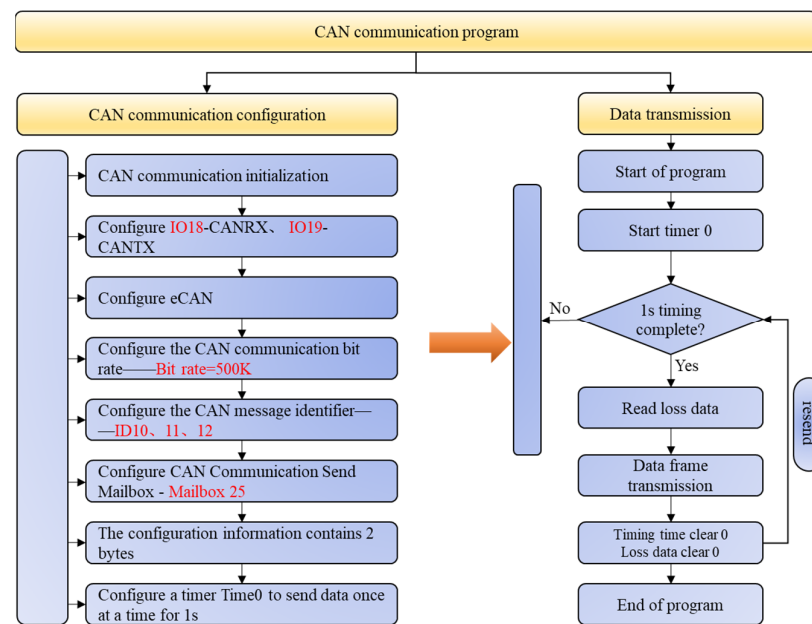


Figure 26. CAN communication configuration and data sending process flow chart.

In the conducted study, the 25th mailbox of the CAN bus was designated as the transmitting mailbox, with data frames being dispatched to the CAN bus network at one-second intervals. To distinctly identify the wheat grain cleaning loss monitored by sensors at three different locations, the identifier (ID) values of the data frames were, respectively, assigned as $0 \times 000A$, $0 \times 000B$, and $0 \times 000C$. Ensuring normal data interaction and accurate transmission necessitates that both the transmitter and receiver agree on the same baud rate. In the context of CAN communication with TMS320F28335, the baud rate is determined using Equations (5)–(7). In the present research, the communication Bit rate has been set to 500 kbps.

$$\text{Bit rate} = \frac{\text{SYSCLKOUT}/2}{\text{BRP} \times (\text{bit time})} \quad (5)$$

$$\text{bit time} = (\text{TESEG1}_{\text{REG}} + 1) + (\text{TESEG2}_{\text{REG}} + 1) + 1 \quad (6)$$

$$\text{BRP} = \text{BRP}_{\text{REG}} + 1 \quad (7)$$

where *Bit rate* indicates the communication bit rate, kbps; *SYSCLKOUT* represents the clock frequency of a single-chip microcomputer system, MHz; *bit time* indicates the bit time, Mbps; *TESEG1*_{REG}, *TESEG2*_{REG}, *BRP*, and *BRP*_{REG} represent the value of the MCU register.

2.4.5. Human–Computer Interaction System

The human–computer interaction system is engineered using development software designed for serial screen compatibility, significantly curtailing the development cycle and diminishing the complexity of the development process. Additionally, the integrated Lua script editor within the development software facilitates efficient secondary development, thereby increasing the convenience of software production. This paper introduces a parametric configuration interface alongside a loss data visualization interface.

Figure 27 illustrates the parameter design interface, wherein the cutting width and rear wheel circumference of the harvester are parameters adjusted according to the specific model of the machinery. Meanwhile, the thousand-grain weight and yield of wheat grains are empirically measured and established before testing. The interface of loss data is shown in Figure 28. Regarding the speed measurement apparatus, as depicted in Figure 29,

it employs a photoelectric sensor in conjunction with a light baffle for velocity detection. Specifically, 16 evenly spaced light baffles are affixed to the inner circumference of the wheat combine's rear wheel. As the harvester propels forward, the rotation of the wheel causes these baffles to pass through the photoelectric sensor, thus generating a low-level signal. This signal, once transmitted into the DSP28335, triggers an external interrupt and initiates the counting routine. The forward velocity of the harvester is subsequently determined using Equation (8).

$$V = \frac{l}{T} = \frac{\frac{L}{N} \times n}{T} = \frac{Ln}{NT} \quad (8)$$

where l is the forward distance of the harvester (m); L is the circumference of the rear wheel of the harvester (m); N is the number of wheel discs in a week, which is set to 16 in this article; n is the number of baffles passing through the photoelectric sensor in unit time; T is the time interval of each speed measurement, which is set to 1 s in this article.

Figure 27. Parameter design interface.

Figure 28 shows the loss data display interface, which is primarily dedicated to exhibiting the number of grains lost as detected by the three position sensors, the aggregate number of lost grains, the mean number of lost grains per square meter, and the overall loss rate. This information is conveyed through the TMS320F28335 processor via the CAN bus to the corresponding display module. By applying Equations (9)–(12), the average number of lost grains and the loss rate per square meter can be further derived. The loss data display interface enables the harvester operator to apprehend the extent of grain loss occurring during the harvesting process directly and offers data-driven support for refining the operational efficiency of the harvesting machinery.

$$S = H \times V \times t \quad (9)$$

$$M_1 = \frac{M}{666.67} \times S \quad (10)$$

$$N = \frac{M_1}{m} \times 10^6 \quad (11)$$

$$Q = \frac{n_1 + n_2 + n_3}{N} \times 100\% \quad (12)$$

where H is the harvester cutting width (m), V is the forward speed of the harvester (m/s), t is the time interval between each loss rate calculation in this article, t is taken as 1 s, S is the harvest area in t time (m^2), M is the yield of wheat in the harvest plot (kg), M_1 is the wheat yield in the working area S (kg), N is the number of wheat grains in the working area S , m is the thousand-grain weight of wheat grain (g), n_1 is the number of lost grains monitored by sensor 1, n_2 is the number of lost grains monitored by sensor 2, n_3 is the number of lost grains monitored by sensor 3, and Q is the cleaning loss rate Q of the wheat harvester in the harvest area S (%).

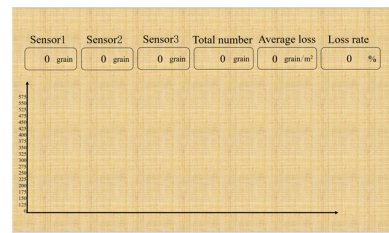


Figure 28. Loss data interface.

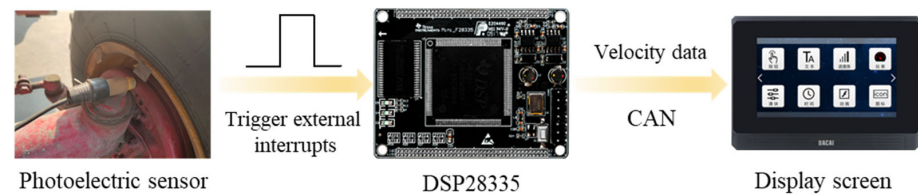


Figure 29. The forward speed measuring device of the harvester.

3. Results

3.1. Bench Test

To investigate the effects of the sensor's angle with the horizontal plane, the height of the sensor's center above the outlet of the aggregate box, and the number of monitored grains on the sensor's monitoring error rate, this study conducted bench tests. The angle and height of the sensor are shown in Figure 30a. Before the bench test, we measured the tail space of the field test machine to ensure it was level, resulting in a maximum measured distance of 500 mm from the bottom of the collection box to the horizontal plane. To guarantee the harvester's ability to navigate complex terrain, including uphill and downhill paths and obstacles, a safety margin of 200 mm was established, setting the maximum sensor installation height at 300 mm.

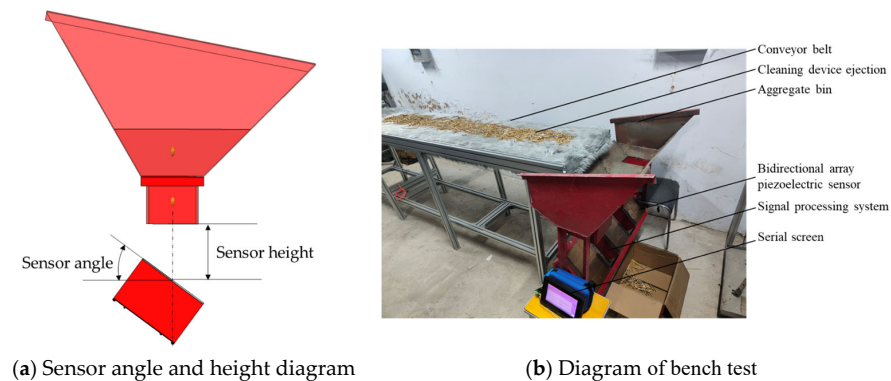


Figure 30. Bench test.

The bench test diagram is shown in Figure 30b. During these tests, the average moisture content of the wheat grains was 13.5%. The grains were evenly distributed on a conveyor belt that was 2.0 m long and 0.3 m wide, moving at a speed of 1 m/s, which meant that all grains completed their collision with the sensor within 2 s. Three-factor and three-level experiments were conducted, considering monitoring grain quantity, sensor angle, and sensor height as factors and monitoring error rate as the performance index, as shown in Table 7 [36–38].

The calculation formula for the error rate is shown in Formula (13).

$$W = \left| \frac{N_1 - N_2}{N_2} \right| \times 100\% \quad (13)$$

where N_1 represents the monitoring loss value of the monitoring device, N_2 represents the actual loss, and W stands for error rate.

Table 7. Coding of simulation test factors.

Code	Experimental Factors		
	Grain Numbers (Grain)	Sensor Angle (°)	Sensor Height (mm)
−1	100	30	100
0	200	45	200
1	300	60	300

The letter A represents the number of grains, B represents the angle of the sensor, and C represents the height of the sensor. The Design-Expert 8.0 software is used to perform variance analysis on Table 8 of the test results. The results of the analysis of variance are shown in Table 9.

Table 8. Experiment scheme and results.

No.	Experimental Factors			Error Rate (%)
	Grain Numbers (Grain)	Sensor Angle (°)	Sensor Height (mm)	
1	−1	0	1	5.4
2	−1	0	−1	6
3	−1	1	0	6.3
4	−1	−1	0	5.7
5	0	−1	−1	6.9
6	0	1	−1	7.7
7	0	0	0	6.2
8	0	−1	1	6.4
9	0	0	0	6.1
10	0	1	1	6.6
11	0	0	0	6.1
12	0	0	0	6.7
13	0	0	0	6.1
14	1	0	1	7.1
15	1	0	−1	7.4
16	1	−1	0	7.5
17	1	1	0	8.6

Table 9. Analysis of variance of regression equations.

Source	Sum of Square	df	Mean Square	F-Value	p-Value
Model	10.12	9	1.12	15.15	0.0008
A	6.48	1	6.48	87.31	<0.0001
B	0.91	1	0.91	12.28	0.0099
C	0.78	1	0.78	10.53	0.0142
AB	0.063	1	0.063	0.84	0.3893
AC	0.022	1	0.022	0.30	0.5990
BC	0.090	1	0.090	1.21	0.3072
A ²	0.14	1	0.14	1.84	0.2173
B ²	1.54	1	1.54	20.77	0.0026
C ²	0.013	1	0.013	0.17	0.6911
Residual	0.52	7	0.074		
Lack of fit	0.25	3	0.083	1.21	0.4129
Errors	0.27	4	0.068		

Note: $p < 0.01$ (highly significant); $0.01 \leq p < 0.05$ (significant); $p \geq 0.05$ (not significant).

Software Design-Expert 8.0 was adopted to perform variance analysis of the data in Table 8. The results are listed in Table 9. It can be seen from Table 9 that the test model is highly significant ($p < 0.01$), suggesting that the designed tests are reasonable and effective; the coefficient of determination R^2 is 0.8884, indicative of a high degree of fitting of the regression equation. The number of wheat grains significantly affected the error rate ($p < 0.01$). The angle between the sensor and the horizontal plane and the distance between the sensor and the outlet significantly affected the error rate ($p < 0.05$). The interaction terms involving the number of wheat grains, the angle of the sensor, and the height of the sensor significantly affect the error rate. The response surface showing the influence of these interaction terms on the error rate is illustrated in Figure 31. Through multiple regression analysis of the test results, the regression equation for the collection rate can be obtained as follows:

$$W = +10.58750 - 0.00345A - 0.21617B - 0.002325C + 0.0000833333AB + 0.0000075AC + 0.0001BC - 0.000018A^2 - 0.00268889B^2 + 0.0000055C^2 \quad (14)$$

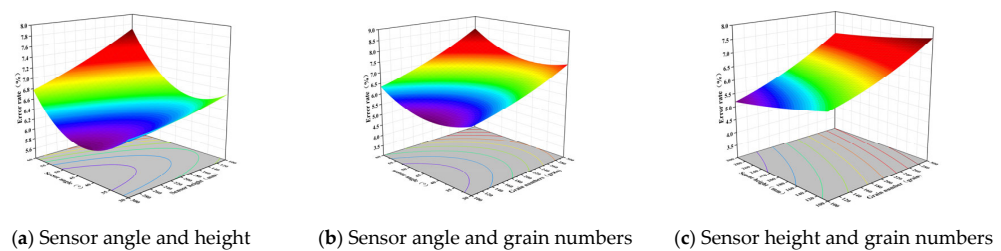


Figure 31. Effect of factor interactions on error rate.

According to the response surface of the pair-to-pair interaction of test factors, it can be seen that when the monitored grain quantity is unchanged, the error rate decreases with the increase in sensor height and then decreases first and then increases with the sensor angle from 30° to 60° , as shown in Figure 31a. When the sensor height remained constant, the error rate increased with the increase in the number of grains and then first decreased and then increased with the sensor angle from 30° to 60° , as shown in Figure 31b. When the sensor angle is unchanged, the error rate increases with the increase in the number of grains and the decrease in the sensor height, as shown in Figure 31c.

Taking the minimum of the error rate as the objective, the optimization module in the software Design-Expert was used to solve the regression equation, thus determining the optimal solution. The equation set of the objective and constraints is expressed as Equation (15).

$$\begin{cases} \text{Min}W(A, B, C) \\ \text{s.t.} \begin{cases} 100 < A < 300 \\ 30 < B < 60 \\ 100 < C < 300 \end{cases} \end{cases} \quad (15)$$

According to the optimized results, when the number of monitoring grains is 100, the angle between the sensor and the horizontal plane is 44.23° (take 44°), and when the height of the sensor from the material outlet is 300 mm, the monitoring error rate is at its minimum, which is 5.19% (as expected based on experimental evidence).

The test value and model prediction value of the error rate under the optimal installation parameters and the relative error are shown in Table 10. The relative error is calculated as shown in Formula 16. The relative errors of the three tests were 1.16%, 0.96%, and 0.19%, and the average relative errors of the three tests were 0.77%.

$$Y = \left| \frac{Y_1 - Y_2}{Y_2} \right| \times 100\% \quad (16)$$

where Y represents the relative error, Y_2 represents the model predicted value, and Y_1 represents the test value.

Table 10. Test value and model prediction value.

No.	Model Predicted Value (%)	Test Value (%)	Relative Error (%)
1		5.25%	1.16%
2	5.19%	5.14%	0.96%
3		5.18%	0.19%

3.2. Field Test

The wheat combine harvester grain cleaning loss monitoring device prototype developed in the present research is installed during the field harvest test. The wheat combine harvester is shown in Figure 32. It is a GE80S (4LZ-8E2) grain combine harvester produced by China's Revo Heavy Industry Co., Ltd. in 2019. The engine power was 121.3 kW, the feed rate was 8 kg/s, and the harvester cutting width was 2.75 m.

**Figure 32.** A wheat harvester model used in the field experiment.

The clearing loss monitoring device is installed at the tail of the harvester, as shown in Figure 33. In early June 2023, a wheat field harvest experiment was carried out in Huojia County, Xinxiang City, Henan Province. The area of each experiment was 2.75 m wide and 30 m long, and the harvest area was 82.5 m². The harvester cut width of the experiment was 2.75 m, that is, each harvester carried out a full-cut harvest of 30 m. The 30 m field where the harvester was tested was divided into three parts: the start-up area of the harvester, the test area, and the parking area of the harvester, 10 m in each area. Field experiments were carried out in three plots (plot 1, plot 2, and plot 3), and each test plot was divided into three 30 m test areas for three repeated tests. The loss data for each plot was averaged and recorded. The wheat varieties in the three test plots were Bainong 4199. Before the test, the 1000-grain weight and yield of the wheat variety Bainong 4199 were measured by a five-point sampling method. The 1000-grain weight of the wheat was 43.21 g, and the yield per mu was 625.83 kg.

**Figure 33.** Installation diagram of the cleaning loss monitoring device.

3.3. Test Result

During the field harvest test, due to the reciprocating motion of the prototype sieve plate, some of the lost grains may be monitored by using the monitoring device, resulting in missed detection. In this paper, five groups of pre-experiments were carried out before the formal harvest test to obtain the missed detection coefficient K . The missed detection coefficient K , wheat yield, and 1000-grain weight were preset as inputs to the human–computer interaction system before the start of the test, and then the field test was conducted.

Through five times of pre-harvest experiments, the missing detection coefficient K is obtained.

$$K = \frac{K_1 + K_2 + K_3 + K_4 + K_5}{5} = 0.87 \quad (17)$$

where K is the average missed kernel coefficient; K_1 , K_2 , K_3 , K_4 , and K_5 are the missed kernel coefficients for each test.

From the pre-test, we determined the missed detection coefficient K to be 0.87. This value was preset in the human–computer interaction system before conducting the field test. Subsequently, the field test was performed (Figure 34). The resulting test data are presented in Table 11.

Table 11. Pre-test data.

Number	Monitoring Losses (Grains)	Measurement Loss (Grains)	Omission Factor K
1	5150	6205	0.83
2	5534	6218	0.89
3	5334	6132	0.87
4	5412	6081	0.89
5	5081	5978	0.85



Figure 34. Field test.

The test results of the field harvest test are shown in Table 12. The monitoring loss represents the grain loss data monitored by the monitoring device, and the actual loss represents the grain cleaning loss data obtained by manual measurement in the collection bag. In test plots 1 and 3, the monitoring data for cleaning loss is smaller than the actual loss, and the monitoring data for test plot 2 is larger than the actual loss. The error rates of the three test plots were 6.19%, 7.93%, and 5.96%, and the average error rates were 6.69%, which met the design requirements of the cleaning loss monitoring device of the wheat combine.

Table 12. Field trial data.

No.	Monitoring Losses (Grains)	Monitoring Loss Rate (%)	Measurements Loss (Grains)	Measurement Loss Rate (%)	Monitoring Error (%)
1	5865	0.98%	6252	1.04%	6.19%
2	6383	1.07%	5914	0.99%	7.93%
3	5763	0.96%	6128	1.03%	5.96%

4. Discussion

The field performance tests of the wheat combine harvester cleaning loss monitoring device developed in this paper show that the number of lost grains monitored is different from the actual loss. The developed prototype, test conditions, and test data were analyzed. The shortcomings of this study are as follows:

- (1) There were differences between wheat grain parameters used in the R & D period and field harvest.

During the field harvest experiment, there will be some parameter differences between the monitored grain and the calibrated grain, such as grain 1000-grain weight, grain water content, and so on. The electrical signals generated by the impact of different parameters on the piezoelectric ceramic will affect the monitoring device, resulting in an inconsistency between the number of lost grains monitored by the monitoring device and the actual number of lost grains, resulting in monitoring errors.

- (2) There was a position difference in the wheat grain impact sensor.

In the study, when the grain collides with the sensor, the electrical signals generated are also different according to the location of the impact. Due to the difficulty in accurately controlling the contact attitude between the grain and the sensor, there is an impact angle deviation and an inaccuracy of the impact position in the actual detection process. For example, if the grain hits the joint of two adjacent piezoelectric ceramic sensors, the generated electrical signal may not be correctly identified by the detection system.

- (3) A few wheat varieties and test areas were analyzed.

The preliminary experiment of this study focused on the monitoring of wheat cleaning loss in specific varieties and regions. Due to the limited number of test varieties and regions, the cleaning loss of the wheat combine harvester under different varieties and regional conditions has not been fully evaluated. To verify the performance and applicability of the wheat combine harvester cleaning loss monitoring device developed in the present study, the next study plan will expand the test range. Through these comprehensive field experiments, the collection of more comprehensive data to evaluate the accuracy, stability, and reliability of the monitoring device is suggested. In addition, the test results will also help to reveal the influences of different varieties and environmental factors on the cleaning loss of the wheat combine harvester and then provide a scientific basis for optimizing the design of cleaning equipment and improving harvest efficiency.

5. Conclusions

Cleaning loss monitoring of wheat combine is one of the key technologies to adjust the parameters of the harvester in real time, reduce the loss of harvest, realize the intelligent harvest operation, and achieve the loss reduction of harvest. Cleaning loss monitoring can obtain kernel loss data in real time, remind the driver to adjust the operation parameters of the harvester in time, reduce the harvest loss, and achieve the purpose of reducing the loss of the machine. Aiming at the need for real-time monitoring of the cleaning loss of wheat combine, this paper developed a monitoring device for the cleaning loss of wheat combine. The main research conclusions are as follows:

- (1) Based on the literature and product data of grain combine loss monitoring devices at home and abroad, this paper expounds and summarizes the grain cleaning loss monitoring technology and method, determines the overall research program and technical route, and carries on the overall design of the wheat combine loss monitoring device. The cleaning loss monitoring device mainly includes a collecting bucket, bidirectional array piezoelectric sensor, vibration signal compensation device, collision signal processing system, human–computer interaction system, etc., which can realize the signal acquisition and identification of the cleaning loss of seeds, display the loss data in real time, remind the driver to adjust the operating parameters of the harvester, and achieve the purpose of collection and loss reduction.

- (2) According to the monitoring requirements of the cleaning loss monitoring device of the wheat combine harvester, the hardware design of the monitoring device was carried out. In order to improve the monitoring capacity of the grain collision sensor and reduce the influence of mechanical vibration on grain recognition accuracy, a bidirectional array piezoelectric sensor and vibration signal compensation device were designed to improve the monitoring capacity of the grain collision sensor. According to the output signal of the sensor, the signal amplifier module is designed, which can realize the signal amplification of 1~100 times. Then, the TMS320F28335 core board is selected as the core processor module, and the collision signals of 20 channels and the vibration signals of 3 channels are collected synchronously through three AD7606 analog-to-digital conversion modules. In order to better transmit the loss data, a CAN communication network is built, and a CAN communication module with a TJA1040 chip as the core is designed to send the cleaning loss data of the combine to the serial screen for data display. According to the power demand of each function module, the power supply circuit is designed to meet the power demand of the cleaning loss monitoring device. The signal amplifier module, AD7606 analog-to-digital conversion module, TMS320F28335 core processor module, and CAN communication module are integrated into the PCB board, and the electrical connection is realized through the PCB board built-in circuit.
- (3) The software design is based on the CCS integrated development environment and Visual TFT serial screen development software. The software design realizes the acquisition, identification, counting, and loss data transmission of wheat kernel collision signals; displays the cleaning loss data on the human–computer interactive system; and realizes the real-time monitoring of the cleaning loss of wheat combine. A multi-channel signal synchronous acquisition program was designed to collect signals from 23 output channels of a bidirectional array piezoelectric sensor and vibration signal compensation device at a sampling rate of 40 kHz, and SPI communication transmitted the collected data to the TMS320F28335 core processor for vibration signal compensation program processing. The kernel identification and counting program with the kernel collision signal peak value of 2.5 V~3.3 V as the index is completed. Finally, the data frames with ID values of 10, 11, and 12 are transmitted to the human–computer interaction system by CAN bus at a communication rate of 500 Kbps for loss data display. When the cleaning loss exceeds the regulation, the driver is reminded to adjust the operating parameters of the harvester to reduce the cleaning loss.
- (4) In order to verify the accuracy, reliability, and stability of the cleaning loss monitoring device, bench tests and field tests were carried out. The bench test shows that the identification error rate of a bidirectional array piezoelectric sensor is 5.19% when the inclination angle is 44° and the center point is 300 mm away from the material outlet. In the field test, the overall operation of the device was stable without any fault. The error rate of kernel identification was less than 8%, and the average error rate was 6.69%, which met the design requirements of the harvester cleaning loss monitoring device and could remind the driver to adjust the operating parameters of the harvester to achieve the purpose of loss reduction.

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