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Article

Design and Test of Self-Leveling System for Cleaning Screen of Grain Combine Harvester

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Abstract: As one of the core working parts of a combine harvester, the cleaning device directly affects the operation performance of the whole machine. This is especially the case on hilly and gently sloping terrain, which, due to the uneven ground, causes the combine harvester body to incline and material to accumulates on one side, resulting in a high cleaning loss rate. To solve this problem, a self-leveling cleaning screen device and a control system based on a fuzzy PID control algorithm are developed for a caterpillar harvester, enabling it to operate on gentle slopes of 10°. To verify the performance of the fuzzy PID algorithm applied to this system, simulation tests, response tests, comparison tests, and field tests were carried out. The indoor test results show that the system has a good tracking effect when the inclination amplitude does not exceed 10°. The maximum leveling error is −0.62°, the maximum leveling time is 1.85 s, and the maximum overshoot is 1.5°. The field test results show that when the tilt angle of the harvester body is within 10°, the system can stabilize the real-time leveling of the cleaning screen. Even with an increase in the tilt angle of the harvester, the cleaning loss of the harvester installed with the automatic leveling system can still be maintained at a low level. The cleaning loss rate of the harvester is 1.2% higher after leveling than during flat operation, which meets the accuracy requirements of the system design. Therefore, this system can be applied to grain combine harvesters and effectively reduce the cleaning loss caused by their operation.

Keywords: grain combine harvester; cleaning screen; self-leveling system; fuzzy control

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1. Introduction

The cleaning device is one of the core working parts of a grain combine harvester, and it directly affects the performance of the whole machine. How to improve the performance and adaptability of the device is the focus of grain combine harvester technology development at this stage [1–3]. China has a vast geographical area, with large areas of hilly and gently sloping terrain and uneven ground which causes the combine harvester's body to tilt and materials to pile up on one side, resulting in a high cleaning loss rate [4]. To improve the screening performance of the cleaning screen, domestic and foreign scholars have carried out a lot of research on the mechanism design and motion control of the cleaning screen.

The cleaning devices of foreign large-scale combine harvesters have achieved automation and can adapt to the needs of different operating environments through the development of new mechanisms. For example, the AGCO S8 series, John Deere C440, and CLAAS LEXION series combine harvesters all use multi-layer vibrating screens to improve cleaning capacity and adaptability through multi-degree-of-freedom motion mechanisms [5,6]. Due to the limitations of planting systems and fields in China, most of the grain combine harvesters developed here are caterpillar types with small feeding amounts. Due to the body size limitations, a multi-layer complex screen body with a multi-degree-of-freedom motion mechanism is rarely used [7–9]. Instead, the focus is mainly improving fan efficiency and reducing airflow attenuation by optimizing the fan structure. Shen and others researched fan structures and parameters with multiple air ducts and outlets and improved screening performance by optimizing the airflow field [10–14]. The 4LZ-5.0E combine harvester produced by Ward Company uses a multi-duct centrifugal separator and a double-layer vibrating screen mechanism to improve the effective screening area and reduce impurities and losses in cleaning, which is fairly effective [15]. Some scholars have also carried out relevant research on multi-dimensional vibrating screens. Wang designed a multi-dimensional vibrating screen device based on a parallel mechanism [16]. Li built a three-dimensional parallel rice vibrating screen model with different initial phases, proposed a screening effect evaluation method, and provided a reference for the selection of the motion form of a multi-dimensional vibrating screen [17]. However, the problem with multi-dimensional vibrating screens is that they generally have complex driving mechanisms and low stability [18], and they have not been put into practical use.

Research on automatic leveling technology started late in China and was first applied in the industrial field. In recent years, it has gradually been applied in the agricultural field. In particular, the continuous improvements in sensor performance have greatly improved the adaptability of automatic leveling systems. The automatic leveling of existing agricultural machinery and equipment is mainly achieved through the combination of mechanics, electro-hydraulic control, attitude perception, and other technologies [19–26].

In this paper, based on the caterpillar-type combine harvester, which has a large market share, an automatic leveling system for the vibrating screen of the combine harvester is designed, and a leveling mechanism and a control system based on the fuzzy PID (proportion integral differential) control algorithm are designed to solve the problem of material accumulation on the vibrating screen during operation on undulating or sloping fields, providing a reference for the cleaning performance of the vibrating screen.

2. System Structure and Working Principle

2.1. System Structure Composition

The self-leveling system of the cleaning device was refitted and designed on a Xingguang 4LZ-5.0Z grain combine harvester (Star Agricultural Machinery Co., LTD., Huzhou, China). Its structural composition is shown in Figure 1: it is mainly composed of an inclination sensor, a controller, a rotating shaft, and an electric cylinder. The inclination sensor, which is used to receive the inclination angle of the harvester body in real-time for field operation, is fixed on the chassis frame. The controller is installed on the driving console. When the cleaning vibrating screen is working, it performs up and down, forward and backward reciprocating screening movements. The screen mesh is hinged with the screen body by the middle rotating shaft and can rotate around the rotating shaft while performing reciprocating screening movement with the cleaning vibrating screen. The electric cylinder can drive the swing rod at one end of the rotating shaft. This causes the screen to rotate left and right to keep it in a horizontal position.

2.2. Working Principle

The controller is connected with the inclination sensor and the distance sensor in the electric cylinder to receive, respectively, the status signals of the combined body and the cleaning vibrating screen in real-time and the output control signals that make the electric cylinder act. The inclination sensor is used to measure the angle between the harvester and the horizontal plane. The electric cylinder is hinged and fixed on the vibrating screen body, and the telescopic end is hinged with a swing rod that can drive the screen to rotate to adjust the screen angle. The displacement sensor is installed inside the electric cylinder to detect any change in the length of the electric cylinder in real-time and determine whether the screen is horizontal according to the relationship between the length of the electric cylinder and the screen angle. The working principle of the system is shown in Figure 2. When the equipment starts to work, the controller receives the signal from the inclination sensor and judges whether the body is tilted. If the body is tilted, the theoretical stroke of the electric cylinder is calculated using the measured value of the inclination sensor and a command is sent to control the electric cylinder and execute the corresponding action. The distance sensor detects the extension distance signal and sends it to the controller. Through the logic operation of the controller, it is determined whether the screen mesh reaches the horizontal position. If it does not reach the horizontal position, it continues to execute the action of the electric cylinder until it reaches the horizontal position, at which point the control ends.

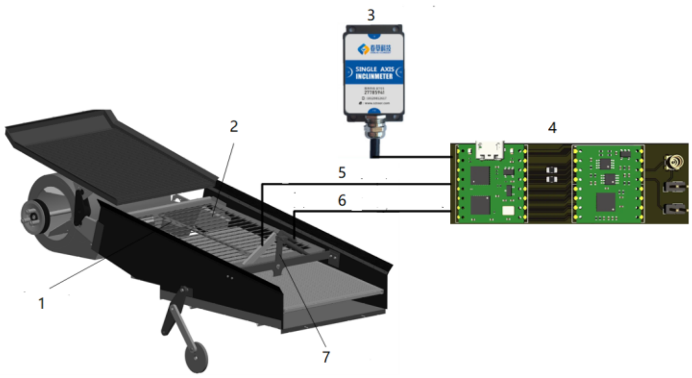

Figure 1. Structural composition of automatic leveling system. 1: rotating shaft; 2: screen; 3: inclination sensor; 4: controller; 5: distance sensor; 6: electric cylinder; 7: swing rod.

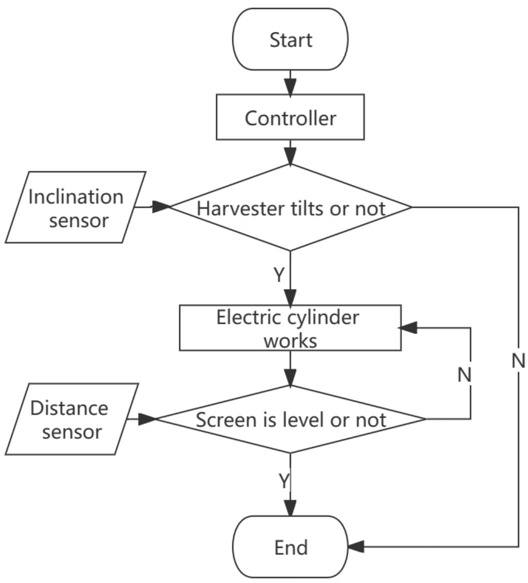

Figure 2. Working principle of the automatic leveling control system for cleaning the vibrating screen.

3. Design of the Automatic Leveling Control System

3.1. Leveling Mechanism Design

The screen body and screen mesh of the traditional cleaning vibrating screen are relatively fixed, and the whole screen moves reciprocally. When the harvester's body inclines, the vibrating screen also inclines, and this causes the material on the screen to pile up on one side. The screen mesh of the cleaning screen designed in this paper is hinged with the screen body by the middle rotating shaft. It can rotate around the rotating shaft while performing reciprocating screening movements with the cleaning vibrating screen. The electric cylinder drives the swing rod at one end of the rotating shaft, thus driving the screen mesh to rotate left and right to keep it in the horizontal position all the time. The electric cylinder is a DDA40-T02-40-BC-TC-G-DY1-C2 servo cylinder from Shenzhen Dingying Intelligent Equipment Co., Ltd., Shenzhen, China, (stroke 40 mm, thrust 0.37 kN, speed 100 mm/s). The lead screw is a ball screw with a lead of 2 mm.

3.2. Dynamic Equation of the Leveling Mechanism

Ignoring the clearance of hinge points, the leveling mechanism is a rigid system, and its simplified structure model is shown in Figure 3. Point A is the fixed hinge point of the electric cylinder, point B is the hinge point of the screen's middle rotating shaft, and point C is the hinge point of the expansion end of the electric cylinder and the swing rod.

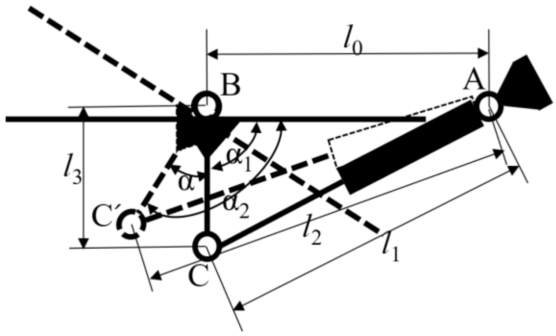

Figure 3. Simplified model of the screen-leveling mechanism.

When the combine harvester's body is horizontal, the electric cylinder does not act, and the length of the electric cylinder is l_1, according to the following cosine theorem:

$$\alpha_1 = \arccos\frac{l_0^2 + l_3^2 - l_1^2}{2l_0l_3} \tag{1}$$

where α_1 is angle between the swinging rod and horizontal plane when the combine harvester is horizontal (°), l_0 is distance between fixed hinge point A of the electric cylinder and shaft center B (m), l_1 is the total length of the electric cylinder when the combine harvester is horizontal (m), and l_3 is the length of the swing rod (m).

When the combine harvester's body inclines and needs leveling, the electric cylinder acts, and the length of the electric cylinder changes from l_1 to l_2, according to the following cosine theorem:

$$\alpha_2 = \arccos\frac{l_0^2 + l_3^2 - l_2^2}{2l_0l_3} \tag{2}$$

where α_2 is the angle between the swinging rod and the horizontal plane when the combine harvester's body inclines (°) and l_2 is the total length of the electric cylinder when the combine harvester's body inclines (m).

According to Equations (1) and (2), the relationship between the tilt angle of the combine harvester's body and the displacement of the electric cylinder is as follows:

$$\alpha = \alpha_2 - \alpha_1 = arccos\frac{l_0^2 + l_3^2 - l_2^2}{2l_0l_3} - arccos\frac{l_0^2 + l_3^2 - l_1^2}{2l_0l_3} \tag{3}$$

3.3. Control System Design

3.3.1. Hardware *Design*

An STM32F103VET6 chip was selected as the core processing module of the cleaning vibrating screen-leveling controller to efficiently process control information. The inclination sensor collects information concerning the inclination of the combine harvester's body and transmits the data to the controller through analog-to-digital conversion. The controller transmits the data processing results to the electric cylinder driver, and the driver drives the electric cylinder to act to adjust the screen posture. Power is provided to the controller by the 24 V battery of the combine harvester, which is used together with 5 V and 3.3 V voltage drop modules.

(1) Inclination sensor sampling circuit

During the operation of the harvester, the body will incline left and right with the changes in terrain. To establish an accurate control model for the leveling of the shale shaker, a single axis current output inclination sensor (an HVS116T from Shenzhen Chuncao Technology Co., Ltd., Shenzhen, China) was selected and installed on the chassis rack of the combine harvester to measure the body inclination angle relative to the ground. The angle measurement range of the sensor is $\pm 30^\circ$ and the output current range is 4–20 mA. When the level is 0°, the output is 12 mA, the resolution can reach 0.001°, and the response time is 0.02 s.

The sensor signal sampling is realized by the analog-to-digital converter (ADC) module inside the processor, and the 3.3 V required for sampling is provided by a Taiwan Youshun (UTC) LR1107G-33-AA3-A-R regulator. The operational amplifier is an LM358 and the scale factor is 1. The internal ADC resolution of the STM32F103 is 12 bits and the minimum accuracy is $3.3/2^{12}$. Finally, the relationship model between the digital sampling quantity and the tilt angle is established as follows:

$$\alpha = \frac{60}{2.4}\left(\frac{2.4}{2^{12}}D - 3.3\right) \tag{4}$$

where, D is the digital quantity after ADC sampling processing

(2) Electric cylinder drive circuit

The STM32F103VET6 chip is used to generate a pulse-width-modulation (PWM) signal to control the stepping motor driver in the electric cylinder and then drive the stepping motor. The stepping motor driver causes the push rod of the electric cylinder to expand and contract by driving the lead screw. The HST1 PUL- and HST1 DIR- are input terminals of the stepping motor driver. The PUL- and DIR- are output terminals of the stepping motor driver. The STM32 chip generates signals and inputs them into the drive circuit on the control board. The HST1 PUL- terminal inputs PWM pulse signals to control the angular displacement when the motor rotates. The HST1 DIR-terminal generates effective levels to control the motor rotation direction to control the extension or shortening of the electric cylinder. After being amplified by the triode on the control board, the control signals are input into the stepping motor by the PUL- and the DIR- in the control signal area of the stepping motor driver so that the stepping motor can be controlled by the stepping motor driver.

3.3.2. Software Design

The automatic leveling control system of the vibrating screen was developed using Keil µVision5. The main cycle program of the software is composed of the upper computer, various sensor communication protocols, and a screen automatic control program. The data transmission is triggered by various interrupts to ensure that the operation of the various programs do not interfere with each other. After initialization is completed and communication is determined to be normal, the system will enter the status of waiting for the interruption. During operation, the data collected by the sensor are sent to the control program through the serial port through the interrupt. After receiving the interrupt request, the system receives the data transmitted by the corresponding serial port and stores them in the buffer zone. The control program then reads the data from the buffer zone and processes them. The processing method is based on the fuzzy PID algorithm. According to the processing results, corresponding instructions are sent from the serial port to the stepping motor driver to drive the stepping motor and to adjust the horizontal angle of the vibrating screen to achieve the effect of leveling. If a tilt occurs again after leveling and the control program has not stopped running, the above steps will be repeated until leveling is again achieved. In the algorithm, the output limit is set for the signal transmitted to the actuator, and the actuator will only adjust within the specified range. The system can also be switched to manual mode, and the upper computer can send signals directly for control. The main program flow chart is shown in Figure 4.

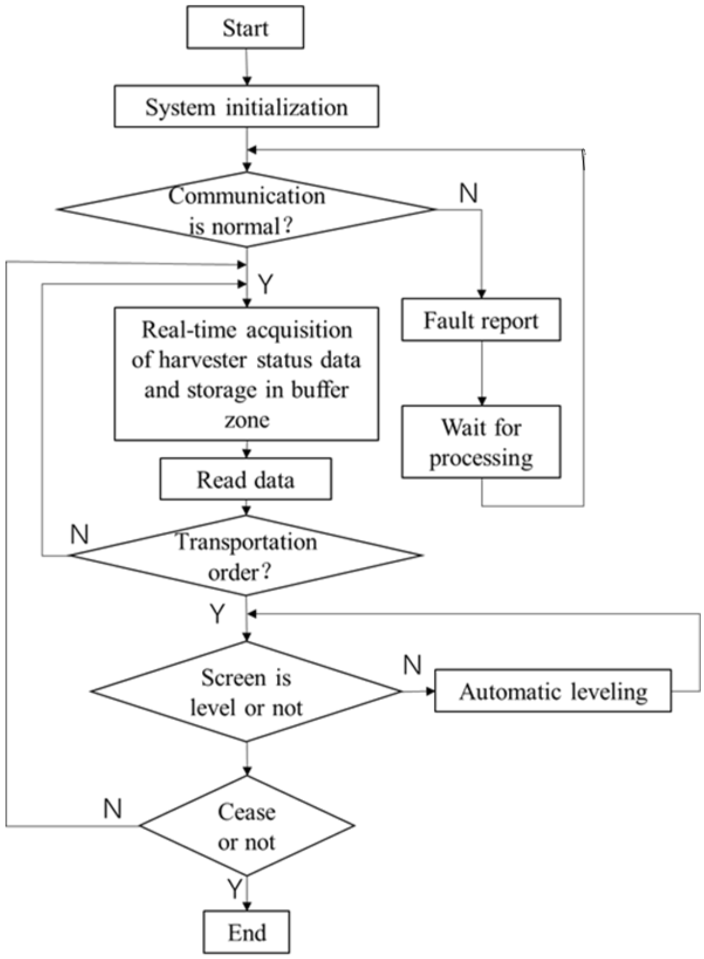

Figure 4. Main program control flow chart.

3.3.3. Filter Design

When the harvester is driving in the field, the control system obtains information concerning the angle of the fuselage through the ADC acquisition circuit. The collected signal is vulnerable to the vibrations of the harvester and the electromagnetic interference generated by other circuits, which affect the control accuracy. To reduce the influence of this kind of noise, it is necessary to introduce a filtering algorithm to filter the sampled values. In this paper, the arithmetic average filtering algorithm is used. The arithmetic average filtering method continuously samples the input signal n times through the embedded processor and calculates the arithmetic average of the results of n original sampling values obtained. The arithmetic expression is given in Formula (5). When the n value is high, the signal smoothness is high, but the sensitivity is low. When the n value is low, the signal smoothness is low, but the sensitivity is high. In this paper, the n value is 4. The arithmetic average filtering method is suitable for filtering signals with random interference. The filtering effect is shown in Figure 5.

$$y = \frac{1}{n}\sum_{i=1}^{n} y_i \tag{5}$$

where y is the arithmetic mean value of n samples, y_i is the ith sampling value, and n is the number of consecutive samples.

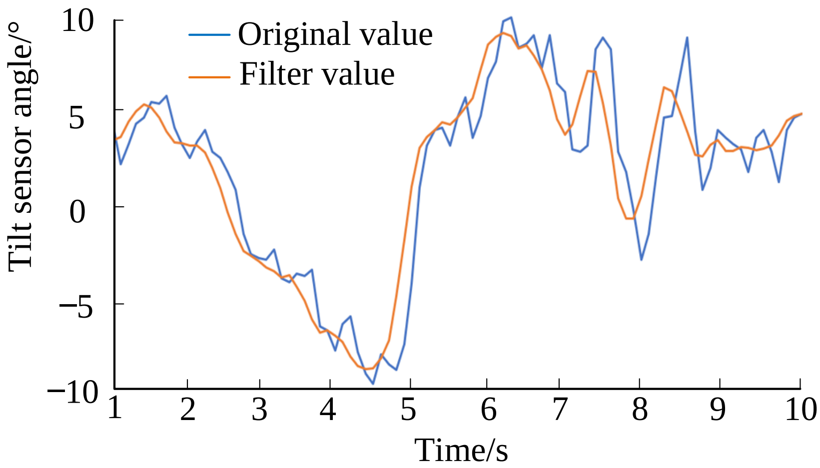

Figure 5. Comparison of sensor filtering effect.

3.4. Control Algorithm

Fuzzy PID Control Algorithm

Due to the poor working environment of the combine harvester, the cleaning vibrating screen is subject to an alternating load during its movement, and this results in uncertainty. A control algorithm combining fuzzy control and PID control was adopted in the design as this can not only eliminate the residual problem under fuzzy control but also solve the problems of long leveling times and large overshoots of the vibrating screen with PID control. Based on the traditional PID linear controller, with the body inclination error and error change rate as the input and the PID parameter adjustment as the output, the PID parameters can be automatically adjusted online through fuzzy control rules. The controller structure is shown in Figure 6 and the workflow is shown in Figure 7.

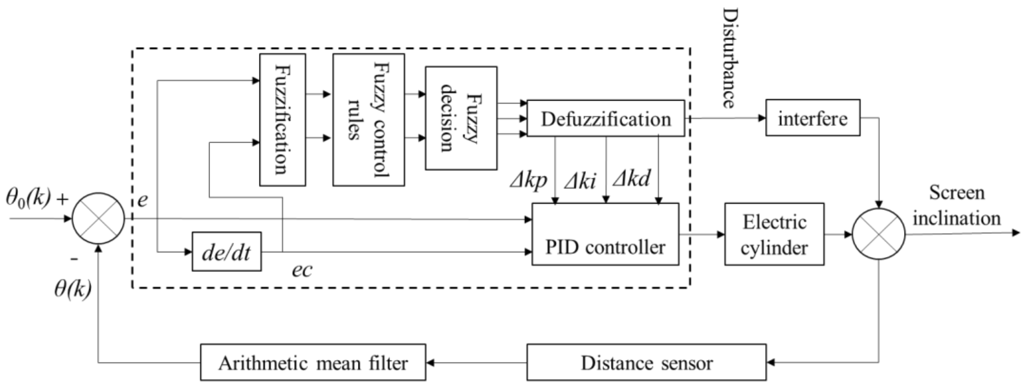

Figure 6. Structure of the fuzzy PID controller.

(1) Input and output variables and their fuzzy universe determination

The fuzzy self-tuning of the PID parameters is intended to find out the fuzzy relationship between the three parameters of PID, *e*, and *ec*. During operation, the three parameters are modified online according to the fuzzy control principle by constantly detecting *e* and *ec*, meeting the different requirements of different *e* and *ec* control parameters, and ensuring that the object is capable of good dynamic and static performance.

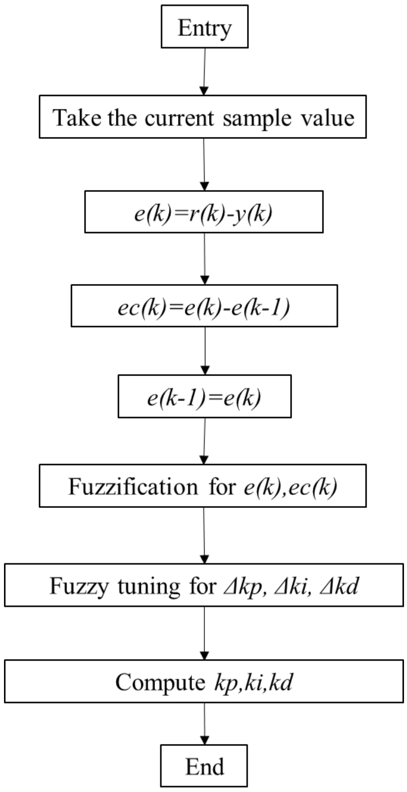

Figure 7. Workflow of the fuzzy PID controller.

The inclination error $e(k)$ of the vibrating screen corresponds to the language variable E. The rate of change of the tilt angle error $ec(k)$ corresponds to the language variable EC. The language variables corresponding to the PID parameter correction $\Delta kp(k)$,$\Delta ki(k)$ and $\Delta kd(k)$ are KP, KI, KD, so the fuzzy controller uses a double input three output mode. The corresponding universe of the controller input and output is set as $(-6, 6)$. The fuzzy subset is set as (NB, NM, NS, Z, PS, PM, PB), representing seven fuzzy states, namely, negative big, negative medium, negative small, zero, positive small, positive medium, and positive big. The magnitude of the corresponding error e and error change rate ec is quantized according to seven grades, which are expressed as $\{-6, -4, -2, 0, 2, 4, 6\}$. The specific parameter settings of the fuzzy PID controller are shown in Table 1.

Table 1. Specific parameter settings of the fuzzy PID controller.

Parameter Name	Language Variable	Basic Universe	Quantization Factor
$E(k)$	E	$(-1.2, 1.2)$	$Ke = 5$
$ec(k)$	Ec	$(-1, 1)$	$Kec = 6$
$\Delta kp(k)$	Kp	$(-1, 1)$	$K\Delta kp = 6$
$\Delta ki(k)$	Ki	$(-0.08, 0.08)$	$K\Delta ki = 75$
$\Delta kd(k)$	Kd	$(-0.1, 0.1)$	$K\Delta kd = 60$

(2) Membership function

To enhance the robustness and sensitivity of the system and improve the response speed of the system, triangular membership functions are used for input and output (Figure 8).

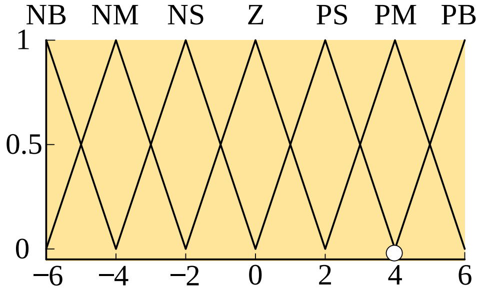

Figure 8. Input and output membership functions.

(3) Establishment of fuzzy rules

Kp, *Ki*, and *Kd* are set according to the set rules of *e* and *ec* at different times and the PID parameters as follows:

(1) When *e* is large, to quickly correct the deviation, the larger *Kp* and the smaller *Ki* and *Kd* should be selected to avoid a large overshoot of the system;
(2) When *e* and *ec* are medium, the smaller *Kp* should be selected to avoid a large overshoot. At the same time, because the value of *Kd* will have a greater impact on the control effect of the system, the smaller *Kp* should be selected to locate *Ki* and *Kd* at a suitable position;
(3) When *e* is small, to ensure the better and more stable performance of the system, *Kp* and *Ki* should both be larger. At the same time, to avoid oscillation of the system at the set value, and considering the anti-interference performance of the system, when *ec* is large, *Kd* can be smaller, and when *ec* is small, *Kd* can be larger. Generally, *Kd* is of medium size. The relationship between the PID regulating parameters and the system time domain performance indicators is shown in Table 2.

Table 2. Relationship between PID regulating parameters and system time domain performance indicators.

Parameter Name	Parameter Change	Rise Time	Overshoot	Transition Time	Static Error
Kp	Enlarge	Reduce	Enlarge	Minor changes	Reduce
Ki	Enlarge	Reduce	Enlarge	Enlarge	Eliminate
Kd	Enlarge	Minor changes	Reduce	Reduce	Minor changes

Based on the above PID parameter setting rules and expert knowledge and experience, the following fuzzy control rule tables (Tables 3–5) for the *Kp*, *Ki*, and *Kd* parameter settings in the automatic leveling control system of the cleaning vibrating screen of the combine harvester studied in this paper are obtained.

Table 3. Adjustment table of *Kp* control rule.

				EC			
E	PB	PM	PS	Z	NS	NM	NB
PB	NB	NB	NM	NM	NM	Z	Z
PM	NB	NM	NM	NM	PS	Z	PS
PS	NM	NM	NS	NS	Z	PS	PS
Z	NM	NM	NS	Z	PS	PM	PM

Table 3. *Cont.*

NS	NS	NS	Z	PS	PM	PM	PM
NM	NS	Z	PS	PS	PM	PB	PB
NB	Z	Z	PS	PM	PM	PB	PB

Table 4. Adjustment table of *Ki* control rule.

				EC			
E	PB	PM	PS	Z	NS	NM	NB
PB	PB	PB	PM	PM	PS	Z	Z
PM	PB	PB	PM	PS	PS	Z	Z
PS	PB	PM	PS	PS	Z	NS	NM
Z	PM	PM	PS	Z	NS	NM	NM
NS	PS	PS	Z	NS	NS	NM	NB
NM	Z	Z	NS	NS	NM	NB	NB
NB	Z	Z	NS	NM	NM	NB	NB

Table 5. Adjustment table of *Kd* control rule.

				EC			
E	PB	PM	PS	Z	NS	NM	NB
PB	PB	PS	PS	PM	PM	PM	PB
PM	PB	PS	PS	PS	PS	Z	PB
PS	Z	Z	Z	Z	Z	Z	Z
Z	Z	NS	NS	NS	NS	NS	Z
NS	Z	NS	NS	NM	NM	NS	Z
NM	Z	NS	NM	NM	NB	NS	PS
NB	PS	NM	NB	NB	NB	NS	PS

(4) PID parameter self-tuning

After obtaining the fuzzy control rule table, according to the input variables (fuzzy quantity) and fuzzy control rules, the output quantity is calculated according to the fuzzy inference rules, that is, the fuzzy inference is carried out according to the fuzzy control rules, and then the output value of the PID parameter adjustment quantity can be obtained by querying the fuzzy control rule table when different deviations and deviation changes arise. However, this value is still a fuzzy quantity and cannot be directly used to modify the PID parameters. In addition, the scale factor must be multiplied to deblur. Thus, the PID parameter tuning Formula (6) is obtained.

$$\begin{cases} K_p' = K_{p0} + K_p \\ K_i' = K_{i0} + K_i \\ K_d' = K_{d0} + K_d \end{cases} \tag{6}$$

In the formula, K_{p0}, K_{i0}, and K_{d0} are the initial values of K_p, K_i, and K_d, respectively, and can be obtained using the trial method. K_p, K_i, and K_d are the outputs of the fuzzy controller, that is, the corrected values of the PID parameters.

4. Tests

4.1. System Test

Under the condition of the test bench, which can be seen in Figure 9, the self-leveling system of the vibrating screen was simulated and tested. By applying the inclination change to the inclination sensor, the angle change of the inclination sensor and the screen mesh angle are monitored in real-time. As is shown in Figure 10, through the system commissioning test, the angle of the shale shaker is determined to be consistent with the angle of the car body, providing good tracking performance. The error is small, i.e., within the ±5° inclination range. If the inclination exceeds 10°, it cannot be followed. The greater the inclination, the worse the tracking performance will be. The results show that the control system has a good tracking effect when the inclination amplitude is not more than 10°, and that it is feasible under actual operating conditions.

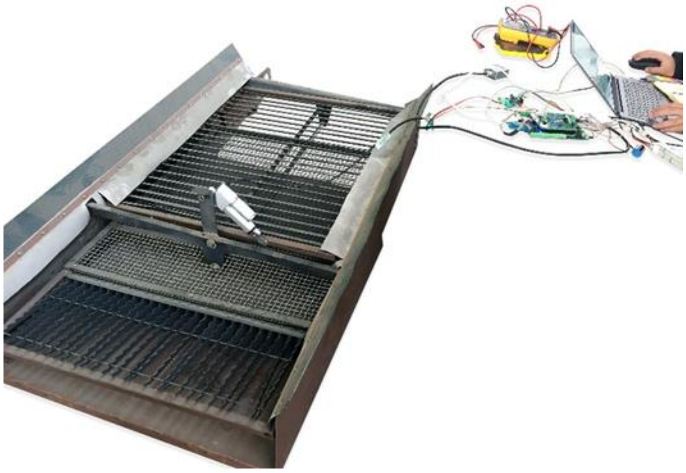

Figure 9. Picture of the test bench.

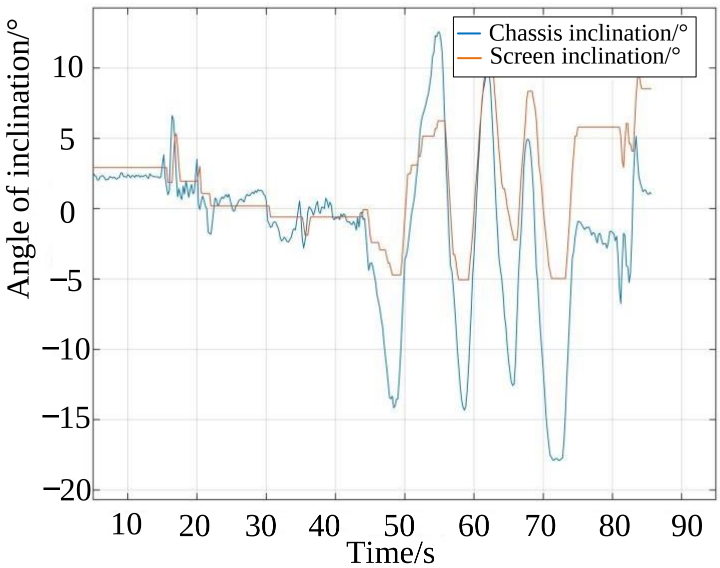

Figure 10. Tracking effect test results.

4.2. System Leveling Response Test

This test is carried out using a manual simulation under real vehicle conditions. The combine harvester is adjusted manually. The left side tilt is defined as a negative value and the right side tilt is defined as a positive value so that its body is tilted at −10°, −7°, −4°, 4°, 7°, and 10°. The body-leveling program is started so that the cleaning vibrating screen is automatically adjusted to the horizontal state. The display angle of the vibrating screen is recorded through the PC program, and the leveling time is recorded using a stopwatch. The timing starts when the leveling procedure is started and ends when the vibrating screen is adjusted to a horizontal and static state. Each group of tests is conducted five times. The test results are shown in Table 5. It can be seen from Table 6 that under six tilt angles the leveling error and the leveling time of the automatic leveling system of the cleaning shale shaker increase with the increase in the vehicle body tilt angle. The maximum leveling error is −0.62°, the maximum leveling time is 1.85 s, the maximum root means square error is 0.034°, and the dispersion is low. The tilt angle error of the cleaning vibrating screen mesh leveled by tilting the left side and the right side of the vehicle body is within ±1°, which meets the horizontal leveling requirements of the combined harvester vibrating screen.

Table 6. System leveling test results.

Inclination/°	Inclination of Screen after Leveling/°	Leveling Time/s	Average Error/°	Root-Mean-Square Error/°	Average of Leveling Time/s
−10	−0.59 −0.60 −0.62 −0.63 −0.65	1.54 1.48 1.44 1.51 1.47	−0.62	0.024	1.49
−7	−0.51 −0.54 −0.52 −0.51 −0.52	1.12 1.11 1.15 1.15 1.14	−0.52	0.012	1.13
−4	−0.37 −0.36 −0.29 −0.35 −0.35	0.82 0.78 0.79 0.84 0.81	−0.34	0.032	0.81
4	0.33 0.29 0.38 0.35 0.36	1.16 1.17 1.10 1.11 1.11	0.34	0.034	1.13
7	0.52 0.51 0.50 0.51 0.52	1.42 1.34 1.41 1.51 1.46	0.51	0.009	1.43
10	0.59 0.62 0.61 0.64 0.59	1.88 1.86 1.82 1.85 1.84	0.61	0.021	1.85

4.3. Static Contrast Test

During the static contrast test, the combine harvester is manually adjusted to make its body tilt at an angle of 10°, the self-leveling programs of the traditional PID algorithm and the fuzzy PID algorithm are started, and the tilt angle of the vibrating screen during the test is collected. The results are shown in Figure 11. Compared with the tilt angle of the vibrating screen controlled by the traditional PID algorithm and the fuzzy PID algorithm, the test results show that the adjustment time of the system under the fuzzy PID control is shorter: the leveling time is about 3 s, which is about 50% shorter than that of the traditional

PID algorithm, and the maximum overshoot is about 1.5°, which is also less than that of the traditional PID algorithm. The static contrast experiment results show that the fuzzy PID control algorithm used in this system has certain advantages in leveling speed over the traditional PID algorithm.

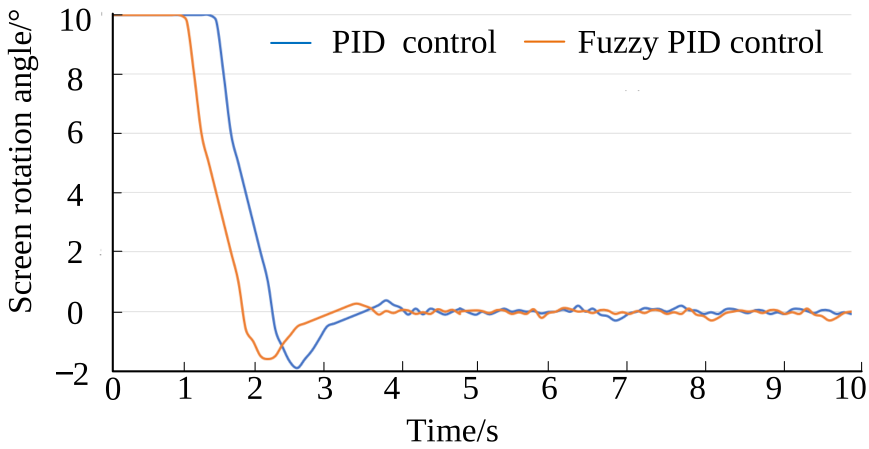

Figure 11. Comparison of PID and fuzzy PID.

4.4. Field Validation Test

The field validation test was conducted in Liyang, Changzhou, on 4 June 2022. The harvested crop was rape, with a height of 2 m, row spacing of 50 cm, plant spacing of 25 cm, and stubble height of 90 cm.

First, a road surface 200 m long is measured at the test site. A 5 m long boss is placed at each end of the road where the left and right tracks pass. The height of the boss is just enough to enable the combine harvester to obtain 4°, 7°, and 10° inclinations. There are 1 m ascending and descending sections at the front and rear ends of the boss which are conducive to the smooth climbing and descending of the tracks. The starting point and ending point are marked and the body inclination values are collected by the controller and sent to the computer through the E62DTU radio data transmission station. Another angle sensor is set on the vibrating screen to detect the screen rotation angle and send it to the computer through the radio data transmission station. When the working parts of the combine harvester do not work, the control system is started, the traveling chassis is driven on the road at a speed of 1 m/s, and the received body inclination value and the corresponding rotation angle value of the screen is recorded. The test results are shown in Figure 12. The results show that the automatic leveling system has a good following effect when the vehicle body angle changes constantly, and that the response time and control accuracy meet the requirements of field operation.

The actual harvest experiment was then conducted in a field (Figure 13). The operation speed of the harvester was set to the middle gear. During the test, ditches were dug to make one side of the combine harvester track run in a ditch and the other side run on the border. Ditches of different depths were dug to form different inclinations for the machine body. The comparative test was carried out in a field with six tilt angles of −10°, −7°, −4°, 4°, 7°, and 10° (Figure 14). During the test, the cleaning loss of the shale shaker was measured both with and without an automatic leveling control system. The cleaning loss was tested according to *The Agricultural Industry Standard of the People's Republic of China—Technical Specification for Quality Evaluation of Rapeseed Combine Harvesters* (NY/T 1231-2006) and *The Agricultural Machinery Extension and Identification Outline—Rapeseed Combine Harvester* (DG/T 057-2011), issued by the Ministry of Agriculture and Rural Areas of the Contract Law of the People's Republic of China. A total of five groups of tilt angle tests were conducted for each type, and the arithmetic mean value was taken as the result (Tables 7 and 8).

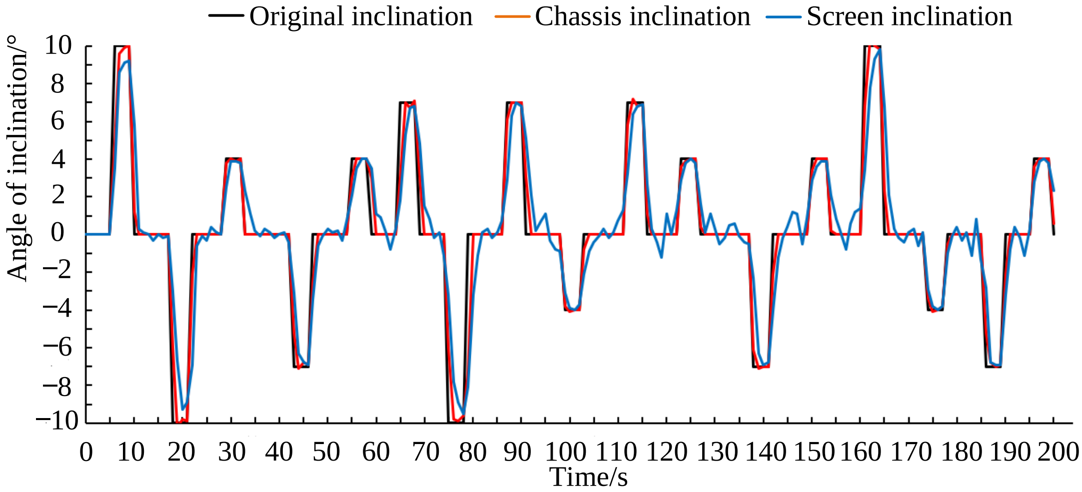

Figure 12. Pavement test results of tracking effect.

Figure 13. Photo of the field validation test.

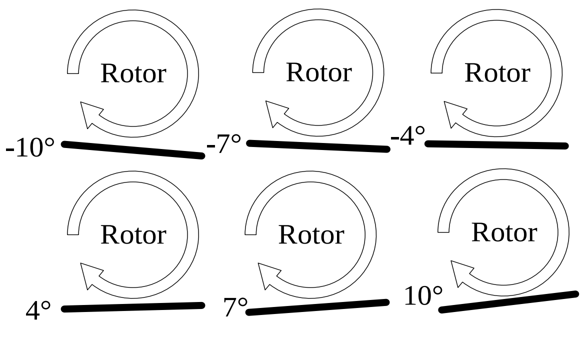

Figure 14. Schematic diagram of the test plan.

Table 7. Cleaning loss without automatic leveling control system.

Inclination/°	Test 1/%	Test 2/%	Test 3/%	Average/%	Standard Deviation/%
−10	6.79	6.68	6.93	6.80	0.125
−7	5.26	5.27	4.92	5.15	0.199
−4	3.49	3.68	3.24	3.47	0.221
0	2.95	3.12	2.96	3.01	0.095

Table 7. *Cont.*

Inclination/°	Test 1/%	Test 2/%	Test 3/%	Average/%	Standard Deviation/%
4	3.37	3.13	3.34	3.28	0.131
7	4.34	4.40	4.52	4.42	0.092
10	5.75	5.82	5.80	5.79	0.036

Table 8. Cleaning loss with automatic leveling control system.

Inclination/°	Test 1/%	Test 2/%	Test 3/%	Average/%	Standard Deviation/%
−10	3.04	2.87	3.03	2.98	0.095
−7	3.00	2.97	2.97	2.98	0.017
−4	3.00	2.96	2.89	2.95	0.056
0	2.88	2.91	2.97	2.92	0.046
4	3.04	2.99	2.76	2.93	0.149
7	2.94	2.87	2.83	2.88	0.056
10	2.79	2.90	2.74	2.81	0.082

The test results show that the cleaning loss of the combine harvester with the automatic leveling control system can be kept at a low level under different tilt angles, while the cleaning loss of the combine harvester without the automatic leveling control system will increase with the increase in tilt angle. This shows that the combine harvester is more likely to suffer from material accumulation on the screen under a large tilt angle, resulting in cleaning loss, and that the automatic leveling control system effectively solves this problem.

5. Conclusions

Based on the crawler harvester, this study developed a self-balancing cleaning screen device and a control system based on the fuzzy PID control algorithm which can adapt to operation on a gentle slope up to 10°, solving the problem of high cleaning loss caused by the accumulation of materials on one side due to the tilt of the machine body when a rape combine harvester operates on hilly or gently sloping terrain. A series of experiments were carried out to verify the effect of the system in the actual working environment

The indoor test results show that the system has a good tracking effect when the inclination amplitude is not more than 10°. The maximum leveling error is −0.62°, the maximum leveling time is 1.85 s, and the maximum overshoot is 1.5°, all of which meet the requirements of field operation.

The field test results show that the automatic leveling system has a good following effect when the body angle changes constantly. When the body angle of the harvester is 10° or less, the system can stabilize the level of the cleaning screen in real-time. Even with an increase in the tilt angle of the harvester, the cleaning loss of the harvester installed with the automatic leveling system can still be maintained at a low level. The cleaning loss rate of the harvester is 1.2% higher after leveling than during flat operation, which meets the accuracy requirements of the system design.

The above experiments jointly verified that the system can effectively reduce the cleaning loss of a grain combine harvester and ensure its stability under actual working conditions. This study also provides a reference for the future design of cleaning devices for other types of combine harvesters.

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References

1. Li, D.; Lu, W.; Wang, X. Research status and development trend of cyclone separating cleaning unit of combine harvesters. *Agric. Equip. Veh. Eng.* **2016**, *54*, 8–13.
2. Xu, L.; Li, Y.; Li, Y. Research progress on cleaning technology and device of grain combine harvester. *Trans. Chin. Soc. Agric. Mach.* **2019**, *50*, 1–16.
3. Hou, J.; Xie, F.; Liu, D. Research progress on air-and-screen cleaning device for combined harvester. *Agric. Eng. Equip.* **2020**, *47*, 12–17.
4. Xiong, W.; Li, Y.; Liu, J. Design and experiment of threshing and cleaning device for hilly rice and rape combine harvester. *J. Agric. Mech. Res.* **2022**, *44*, 167–171.
5. Chen, Z.; Gao, L.; Chen, C. Analysis on technology status and development of peanut harvest mechanization of china and the united states. *Trans. Chin. Soc. Agric. Mach.* **2017**, *48*, 1–21.
6. Wellington, C.K.; Bruns, A.J.; Sierra, V.S.; Phelan, J.J.; Hageman, J.M.; Dima, C.; Boesch, H.; Herman, H.; Pezzementi, Z.A.; Male, C.R.; et al. Grain Quality Monitoring. U.S. Patent 9779330, 26 December 2014.
7. Li, J.; Zhao, D.; Shen, H. Research on screening effect of grain three dimensional parallel vibrating screen based on DEM. *China Mech. Eng.* **2013**, *24*, 1018–1022.
8. Wang, C.; Li, Y.; Ma, L. Design of three degree of freedom hybrid vibration screen. *Trans. Chin. Soc. Agric. Mach.* **2011**, *42*, 69–73.
9. Li, H.; Li, Y.; Tang, Z. Test study on cleaning performance of air and screen cleaning mechanism. *Chin. Agric. Mech.* **2010**, *6*, 54–57.
10. Shen, D.; Li, B.; Sun, L. Shuangfengdao qingxuan zhuangzhi zai guwu lianhe shouhuoji shang yingyong [Application of double air duct cleaning device on grain combine harvester]. *Nongye Jixie Xuebao* **1995**, *4*, 151–155.
11. Xu, L.; Yu, L.; Li, Y. Numerical simulation of internal flow field in centrifugal fan with double outlet and multi-duct. *Trans. Chin. Soc. Agric. Mach.* **2014**, *45*, 78–86.
12. Liang, Z.; Li, Y.; Mam, P. Structure optimization and experiment on cleaning system in longitudinal-axial combine harvester. *J. Agric. Mech. Res.* **2018**, *40*, 70–174.
13. Liang, Z.; Li, Y.; Zhao, Z. Monitoring mathematical model of grain cleaning losses on longitudinal-axial flow combine harvester. *Trans. Chin. Soc. Agric. Mach.* **2015**, *46*, 106–111.
14. Yuan, J.; Yang, J.; Wan, X. Design and experiment of cylinder sieve type re-cleaning device for rape combine harvester. *Trans. Chin. Soc. Agric. Mach.* **2022**, *53*, 99–108.
15. Wang, C.; Li, Y.; Ma, L. Design of multi-dimensional vibration screening test bench based on parallel mechanism. *Trans. Chin. Soc. Agric. Mach.* **2012**, *43*, 70–74.
16. Li, Y.; Liu, X.; Ma, Z. Investigation on three-dimensional parallel screening performance based on initial phase of different branches. *Trans. Chin. Soc. Agric. Mach.* **2017**, *48*, 88–95.
17. Dai, F.; Fu, Q.; Zhao, W. Design and test of double duct system of air-screen separating and cleaning machine for flax threshing material. *Trans. Chin. Soc. Agric. Mach.* **2021**, *52*, 117–125.
18. Xu, L.; Li, Y.; Zhang, L. Development on test-bed of axial threshing and cleaning unit. *Trans. Chin. Soc. Agric. Mach.* **2007**, *12*, 85–88.
19. Chen, X.; Wu, C.; Zhang, M. Development status and trend analysis of rapeseed combine harvester in China. *J. Chin. Agric. Mech.* **2018**, *39*, 28–31.
20. Wei, L.; Che, Y.; Wang, F. Design and experiment of the ground profiling control system of combine header. *J. Agric. Mech. Res.* **2017**, *39*, 150–154.
21. Chen, J.; Lian, Y.; Li, Y. Real-time grain impurity sensing for rice combine harvesters using image processing and decision tree algorithm. *Comput. Electron. Agric.* **2020**, *175*, 194–199. [CrossRef]

22. Kowbel, W.; Xia, X.; Champion, W. PZT/polymer flexible composites for embedded actuator and sensor application. *Proc. SPIE* **1999**, *3675*, 32–34.
23. Gorial, B.; Callaghan, J. Separation of Grain Straw in a Vertical Air Stream. *J. Agric. Eng. Res.* **1991**, *48*, 111–122. [CrossRef]
24. Li, J.; Zeng, Q.; Deng, J. Screening process analysis for multi-dimensional parallel vibrating screen and optimization of screen surface movement. *Trans. Chin. Soc. Agric. Mach.* **2016**, *47*, 399–407.
25. Chen, Q.; Han, Z.; Cui, J. Development status and trend current situation of self-propelled combine harvester. *J. Agric. Sci. Technol.* **2015**, *17*, 109–114.
26. Li, Q.; Song, Y.; Yao, C. Intelligent design and optimization system for cleaning device of rice and wheat combine harvester. *Trans. Chin. Soc. Agric. Mach.* **2021**, *52*, 92–101.