Monitoring method and test of wheat harvester loss rate based on PVDF sensor

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Abstract. Aiming at the problem that the cleaning loss of wheat harvester affects the harvesting quality, we developed a loss detection system based on PVDF (polyvinylidene fluoride) piezoelectric film cleaning loss sensor. After the study of the relationship between the impact speed and the piezoelectric effect of the scavenging screen, the filtering method for discriminating the grain signal is found. The effect of fan speed on grain quality distribution behind the clearance screen of longitudinal axial flow wheat harvester was studied. The results showed that the effect of fan speed 1100~1200r/min on grain quality distribution was not obvious. The optimum monitoring area of the sensor was found by studying the distribution law of grain quality of the clear separation loss, and the mathematical model of the monitoring of the cleaning loss was established. The result of the model test showed that the deviation of the model was less than 1.169, and the accuracy of the model was higher. This paper presents a method for calculating the cleaning loss rate based on the feed rate of the combined harvester. The influence of the feed rate on the monitoring accuracy of the cleaning loss rate was studied by bench test. The relative error of the monitoring results is between 1.84% and 3.15%, which indicates that the combined harvester cleaning loss monitoring system developed in this paper has a high monitoring accuracy.

1. Introduction

Cleaning loss refers to the number of grains mixed in the screenings of combine harvester (Jie, 2009; Zhao et al., 2011), which is generally measured by the rate of cleaning loss. It is an important index to evaluate the quality of harvester operation. Excessive cleaning loss will inevitably increase the loss of wheat harvest and reduce the economic benefits of farmers. In order to prevent the emergence of this problem, many domestic experts and scholars have conducted a lot of research on its monitoring technology and method. For example, Chen (2011) from China Agricultural University studied the law of the influence of feeding amount on the loss rate of combine harvester and established a mathematical model, the method indirectly monitors the cleaning loss by monitoring the feeding amount, but the actual factors affecting the harvest loss include not only the feeding amount, but also the rotational speed of the drum, threshing clearance, air flow size and other factors, so its promotion and use are greatly restricted. Zhou et al. (2010) of the Chinese Academy of Agricultural Mechanization developed a PVDF array cleaning loss detection sensor, by adjusting the sensor signal, the pulse signal number of grain impact plate was obtained to determine the grain loss; Li et al. (2012) from Jiangsu University developed an online monitoring and alarming system for cleaning loss by...
using piezoelectric ceramic sensor as sensing element and secondary instrument as display; Liang et al. (2015) developed a grain loss monitoring system with high precision, a monitoring model of rice cleaning loss was established. In conclusion, most of the studies on sorting loss are based on collecting the vibration frequency of grain impact plate, filtering it to get the signal of grain impact and counting, and ultimately determining the amount of grain loss. But the feeding quantity of harvester fluctuates, which makes it impossible to accurately describe the amount of loss and the quality of harvester operation. Therefore, this paper carried out research on sensor monitoring technology and method of wheat harvester loss rate.

2. Study on Detection Method of Cleaning Loss

In order to real-time monitor the grain loss caused by the cleaning process of combine harvester and display it in real-time in the form of loss rate, this paper developed a monitoring system of grain loss based on impact principle, the monitoring principle is shown in figure 1. Identification of hybrid grains in effluent by calibrating threshold difference between strike speed and sensor output voltage. The physical model between the seed impact signal and the amount of loss was established by studying the distribution law of lost grains behind cleaning screen, which provided a basis for the online monitoring of the amount of loss. In order to ensure that the selected monitoring points are representative, the model errors of each point are further analyzed and compared to determine the optimal detection location of the detection sensor. The relationship between the total amount of lost grains and the amount of feed was analyzed, and the Grain cleaning loss was converted into the rate of loss grains.

### Figure 1. Schematic diagram of Monitoring system

2.1. Sensor selection

The commonly used piezoelectric impact sensors are piezoelectric ceramic type and piezoelectric thin film type (Ju et al., 2004). Because the piezoelectric constant of PVDF piezoelectric film is larger than that of piezoelectric ceramic sensor, it has better voltage output characteristics, and the piezoelectric film has good machinability, the size is determined according to the need, and can withstand large bending deformation. Therefore, the DT series PVDF piezoelectric film sensor of American MEAS brand was selected in this paper to monitor the cleaning loss. The sensor is 52um thick and soft, so this study selected 3mm thick steel plate as the mounting bracket, and the sensor is pasted on the bracket. In order to avoid the monitoring error caused by the secondary ejection between the grains and the mounting bracket, EVA foam double-sided rubber vibration isolation method is adopted between bracket and sensor to reduce noise, so as to ensure the monitoring accuracy of sensor, as shown in Figure 2.
In order to control the detection noise caused by machine vibration, the rubber sheet is used to isolate vibration at the joint of the impact plate and the harvester frame to further improve the detection accuracy of the sensor. Considering that the small mass of the discharged material from the cleaning screen may lead to the problem that the impact signal is too weak to distinguish between the grain and the miscellaneous signal, a signal amplification module as shown in FIG. 3 is added in the system to amplify the output voltage of the piezoelectric thin film. The working voltage of this module is 5~9V, and the dynamic magnification is adjustable from 0 to 1000 times, which can effectively improve the resolution accuracy of the system.

3. Research on the monitoring model of cleaning loss

3.1. Calibration of seed impact signal
It is necessary to calibrate the impact signals of different impurities on the monitoring system in order to distinguish the impact signals of seeds from the impact signals of many sundries. According to the four components of grain, glume shell, shorter stalk and longer stalk, the effects of different impurity impact strength on the output signal were tested in laboratory in advance, which provided a basis for the calibration of seed impact signal. In this experiment, Jimai 22, the largest planting area in Shandong province, was selected as the experimental object to study the sensor output voltage of grain, glume shell, short stalk (< 10cm) and long stalk (> 10cm) under different impact velocity conditions. The test results are shown in FIG. 4 below. The glume shell is ignored because its floating speed is too small and it has too little impact on the sensor and the output voltage generated by its impact is too small. When the impact velocity of grain is 1.7-2.5m /s, the output voltage of grain is 2-3.3V, which is obviously different from the long and short stalk impact signal voltage of 0.1-1.2v. Therefore, the software filtering threshold is determined accordingly.

![Figure 2. Sensor for cleaning loss](image)

![Figure 3. Amplifier for module charge](image)

![Figure 4. Related curve between striking speed and output](image)
3.2. Research on mathematical model of grain mass distribution probability

The cleaning loss of the wheat harvester is distributed in a large area after Cleaning screen, so it is difficult to conduct comprehensive and accurate monitoring. Therefore, this study adopts the discrete point method for monitoring. Considering the inhomogeneity of the loss grain distribution in the longitudinal and transverse directions, the loss grain distribution law of cleaning was studied and a monitoring mathematical model was established. The threshing and cleaning test bench used in the experiment is based on the 4LZ-10 wheat harvester developed by Shifeng Group. It is mainly composed of threshing drum, concave plate screen, cleaning screen and fan, and its structure is shown in figure 5.

When working, wheat by conveying the bridge into the longitudinal axial flow threshing and separating drum for threshing, the wheat is separated from the stalk by the impact and rubbing of the concave plate and the ripple bar. The stalk moves backwards with the rotation of the threshing drum to complete the cyclic threshing of the grains without threshing and the separation of the grains from the stalks, which take off grain and some miscellaneous through separating concave plate into the cleaning system, while long stalk discharge outside. Cleaning system is mainly composed of cleaning screen and fan, most of the grains entering the cleaning screen are dropped from the cleaning screen hole, collected and sent to the granary. A small part of grains are discharged from the culm along with other impurities under the action of fan airflow and cleaning screen. This part of loss, together with the unseparated grains in the culm, forms the cleaning loss described in this study.
Before the experiment, the cutting table of harvester and the culm shredding and throwing device were unloaded, and a receiving box was installed at the tail of the cleaning screen. The position of the receiving box was equal to the tail of the cleaning screen. The distribution of the lost grains was determined by weighing the grains in the receiving box. Set the axis direction of the longitudinal flow threshing drum as y axis and its vertical direction as x axis, and the lower left corner of the receiving box as the origin of coordinates O to establish the coordinate axis, as shown in FIG. 6. The receiving box is divided into 12 horizontal grids and 8 vertical grids, with each grid size of 100×100×200mm. It can be seen from the literature (Li, 2013) that the fan speed is the significant factor affecting the loss grain distribution under the specific threshing and cleaning structure. Therefore, the fan speed was set as 1100r/min, 1200r/min, and 1300r/min in the test. The test conditions were 8kg/s feeding, 800r/min drum speed, 250r/min screen cleaning crankshaft speed, and the average value is obtained three times in each group.

During the experiment, wheat harvested from the field was evenly placed on the conveyor belt. The test bench was started and when it was running smoothly, the conveyor belt was opened to adjust the feeding amount of 8kg/s of the simulated harvester. At the end of each experiment, the grains in the box were cleaned and the clean grains were obtained and called their mass \( m(x_i, y_j) \). The total quality of the lost grains was obtained by adding up the quality of the grains in all receiving boxes:

\[
M = \sum_{i=0}^{12} \sum_{j=0}^{12} m(x_i, y_j). \]

The proportion of grain quality in each square:

\[
\text{proportion} = \frac{m(x_i, y_j)}{M} \times 100\%. \]

The percentage of grain quality in each grid was calculated, as shown in table 1, table 2 and table 3 below.

**Table 1. Distribution of the clear grains in the receiving box in 1100 r/min**

| Y serial number | The x axis serial number |
|-----------------|--------------------------|
| 1               | 2.712 2.437 2.175 2.077 1.920 1.891 1.851 1.867 1.885 1.974 2.032 2.241 |
| 2               | 2.347 2.073 1.798 1.700 1.544 1.514 1.475 1.490 1.509 1.597 1.655 1.864 |
| 3               | 1.936 1.662 1.387 1.289 1.132 1.103 1.063 1.079 1.097 1.186 1.244 1.453 |
| 4               | 1.728 1.454 1.179 1.081 0.925 0.895 0.856 0.871 0.890 0.978 1.036 1.245 |
| 5               | 1.487 1.212 0.938 0.840 0.683 0.654 0.614 0.629 0.648 0.736 0.794 1.004 |
| 6               | 1.281 1.007 0.732 0.634 0.477 0.448 0.408 0.424 0.442 0.531 0.589 0.798 |
| 7               | 1.147 0.872 0.598 0.500 0.343 0.314 0.274 0.289 0.308 0.396 0.455 0.664 |
| 8               | 0.767 0.493 0.218 0.120 0.056 0.026 0.000 0.009 0.020 0.017 0.075 0.284 |

**Table 2. Distribution of the clear grains in the receiving box in 1200 r/min**

| Y serial number | The x axis serial number |
|-----------------|--------------------------|
| 1               | 2.668 2.394 2.131 2.033 1.877 1.847 1.808 1.823 1.842 1.930 1.988 2.197 |
| 2               | 2.314 2.039 1.765 1.667 1.510 1.481 1.441 1.457 1.475 1.563 1.622 1.831 |
| 3               | 1.910 1.635 1.361 1.263 1.106 1.077 1.037 1.052 1.071 1.159 1.218 1.427 |
| 4               | 1.718 1.444 1.169 1.071 0.915 0.885 0.846 0.861 0.880 0.968 1.026 1.235 |
| 5               | 1.492 1.218 0.943 0.845 0.688 0.659 0.619 0.635 0.653 0.742 0.800 1.009 |
| 6               | 1.292 1.018 0.743 0.645 0.489 0.459 0.420 0.435 0.454 0.542 0.600 0.809 |
| 7               | 1.167 0.892 0.618 0.520 0.363 0.334 0.294 0.309 0.328 0.416 0.474 0.684 |
| 8               | 0.869 0.594 0.320 0.222 0.065 0.036 0.004 0.019 0.030 0.118 0.177 0.386 |
Table 3. Distribution of the clear grains in the receiving box in 1300 r/min

| Y the serial number | The x axis serial number |
|---------------------|--------------------------|
|                     | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12  |
| 1                   | 2.637| 2.362| 2.100| 2.002| 1.845| 1.816| 1.792| 1.810| 1.899| 1.957| 2.166|
| 2                   | 2.293| 2.019| 1.744| 1.646| 1.490| 1.460| 1.421| 1.436| 1.454| 1.543| 1.601| 1.810|
| 3                   | 1.896| 1.622| 1.347| 1.249| 1.093| 1.063| 1.024| 1.039| 1.057| 1.146| 1.204| 1.413|
| 4                   | 1.709| 1.435| 1.160| 1.062| 0.906| 0.876| 0.837| 0.852| 0.870| 0.959| 1.017| 1.226|
| 5                   | 1.498| 1.224| 0.949| 0.851| 0.695| 0.665| 0.626| 0.641| 0.660| 0.748| 0.806| 1.015|
| 6                   | 1.303| 1.028| 0.753| 0.656| 0.499| 0.469| 0.430| 0.445| 0.464| 0.552| 0.610| 0.819|
| 7                   | 1.193| 0.919| 0.644| 0.546| 0.390| 0.360| 0.321| 0.336| 0.354| 0.443| 0.501| 0.710|
| 8                   | 0.899| 0.624| 0.350| 0.252| 0.095| 0.066| 0.034| 0.049| 0.060| 0.148| 0.206| 0.416|

The percentage of grain quality distribution under each wind speed was cumulated vertically and horizontally to obtain the probability of grain distribution along the horizontal and vertical lines, such as table 4 and 5. The significance test showed that the fan speed had little influence on the grain distribution law of wheat when it was in the range of 1100~1300r/min, and the mathematical model under this condition was established.

Table 4. Transverse Distribution of Grain for different Fan rotational speeds

| The x axis serial number | Fan speed (r/min) |
|--------------------------|------------------|
|                          | 1100             | 1200 | 1300 |
| 1                        | 13.7794          | 13.4306| 13.0303|
| 2                        | 11.4326          | 11.2338| 10.9335|
| 3                        | 9.3679           | 9.0491 | 8.7488 |
| 4                        | 8.3655           | 8.2667 | 7.9664 |
| 5                        | 7.3116           | 7.0131 | 6.8128 |
| 6                        | 6.9759           | 6.7771 | 6.5768 |
| 7                        | 6.2675           | 6.4687 | 6.6684 |
| 8                        | 6.3892           | 6.5911 | 6.7908 |
| 9                        | 6.4311           | 6.7323 | 7.032 |
| 10                       | 7.3375           | 7.4387 | 7.7384 |
| 11                       | 7.5031           | 7.9043 | 8.104 |
| 12                       | 9.2751           | 9.5771 | 9.9768 |

Table 5. Longitudinal Distribution of Grain under different Fan rotational speed

| Y the serial number | Fan speed (r/min) |
|---------------------|------------------|
|                     | 1100             | 1200 | 1300 |
| 1                   | 23.5371          | 24.5383| 25.783|
| 2                   | 19.1633          | 20.1645| 21.1624|
| 3                   | 12.7148          | 15.3153| 15.951 |
| 4                   | 12.4161          | 13.0173| 13.871 |
| 5                   | 9.3017           | 10.3029| 11.3062|
| 6                   | 6.6041           | 7.9053 | 9.150 |
| 7                   | 5.3969           | 6.3981 | 7.7987 |
| 8                   | 1.6385           | 2.8397 | 3.8349 |
MATLAB was used to carry out polynomial fitting on the data in the above two tables, and the mathematical model (1) of grain distribution probability along the horizontal and the mathematical model (2) of grain distribution along the vertical were obtained respectively. The fitting curves were shown in FIG. 7 and FIG. 8 respectively. By fitting curve can be seen in the x axis between 0.6 ~ 0.8 m Δmi is less than 0.4009 (i.e. horizontal 7, 8 lines, Δmi for the ith row material box in a maximum of three kinds of wind speed under the condition of grain quality error), 0.3m to 0.4 m of y axis Δmj is less than 0.4559 (that is, vertical column 4, Δmj is the maximum value of grain quality error under three wind speed conditions of the junction box in row j) the minimum error limit of grain quantity distribution under different wind speed of the fan. Thus, it is determined that the more accurate monitoring value can be obtained by installing the sensor until (4, 7).

\[
\begin{align*}
  f(x) &= 13.685x^4 - 40.091x^3 + 55.555x^2 - 38.728x + 16.875 \\
  f(y) &= -50.194y^3 + 97.587y^2 - 76.33y + 31.354
\end{align*}
\]

(1) (2)

Horizontal and vertical integrals were performed on the sensor monitoring area to obtain the percentage of lost grains in the monitoring area U:

\[
U = \int_{x_0}^{x_0+b} f(x)dx \int_{y_0}^{y_0+a} f(y)dy
\]

(3)

where

- \(x_0\) is the transverse distance between the sensor and the tail of the cleaning screen, m;
- \(y_0\) is the longitudinal distance between the sensor and the tail of the cleaning screen, m;
- \(a\) is the length of sensor, m;
- \(b\) is the sensor width, m;
- \(\alpha\) is the installation angle between the sensor and the horizontal plane.

### 3.3. Inspection and Modification of Cleaning Loss Monitoring Model

By formula (3), the percentage of loss in the area where the receiving box (4, 7) (i.e. transverse grid 7, longitudinal grid 4) and the receiving box (4, 8) are respectively calculated, and the deviation between them and the actual value is compared:

\[
e = \left| \frac{U(x_0,y_0) - n(x_0,y_0)}{U(x_0,y_0)} \right| \times 100\%.
\]

As shown in table 6, it can be seen that the deviation between the calculation result of the model and the actual value is 0.754% ≤ \(e\) ≤ 1.169%, the established model is relatively accurate and does not need to be revised.
3.4. Research on calculation method of cleaning loss rate

The value measured by the sensor is the actual grain loss in the monitoring area, and the ratio of it to formula (3) can obtain the total grain loss per unit time H:

\[ H = \frac{S}{U} \]  \hspace{1cm} (4)

where

- \( S \) = the monitoring value within the sensor monitoring time \( t \);
- \( U \) = the value measured by the sensor.

The total quality of grain loss \( W \) is obtained by multiplying the total grain loss with the grain weight:

\[ W = H \times p \times 10^6 \times (1 - \frac{k}{100}) \]  \hspace{1cm} (5)

where

- \( p \) = the thousand-grain weight of seeds, which is measured by the test, g;
- \( k \) = the grain moisture content, %.

The ratio of the grain loss quality \( W \) to the total grains harvested by the harvester can obtain the grain cleaning loss rate \( L \):

\[ L = \frac{W}{Q \cdot v \cdot d \cdot t} \times 100\% = \frac{p \cdot S \times 10^6 \times 100\%}{Q \cdot v \cdot d \times (1 - 0.01k)} \times \frac{100\%}{U} \]  \hspace{1cm} (6)

where

- \( Q \) = the yield per unit area of wheat, kg/m²;
- \( v \) = the operation speed of the harvester, m/s;
- \( d \) = the operating width of the harvester, m;
- \( t \) = the design time interval for the system, s.

4. Experiment

The cleaning loss monitoring system developed in this paper is installed on the above threshing and cleaning test bench, as shown in FIG. 9.

Figure 9. Experiment table for threshing and cleaning

The transverse distance \( x_0 \) between the sensor and the tail of the cleaning screen was 0.7m, and the longitudinal distance \( y_0 \) from the tail of the screening screen was 0.3m, the length of the sensor \( a \) was 0.03 m, the width of the sensor \( b \) was 0.05m, the angle \( \alpha \) between the sensor and the horizontal plane was 30 degrees. Before the test, the 1000-grain weight \( p \) was 38.4g, the grain moisture content \( k \) was...
17.2%, and the system time \( t \) was set as 2s (the system refreshed the loss rate once with the frequency of 2s). The above parameters were substituted into equation (6) to obtain:

\[
L = \frac{W}{Q} \times 100% \\
= \frac{S \times 38.4 \times 10^{-6}}{2Q \times 0.808 \times \sqrt{\frac{172}{f(x)}} \times \sqrt{\frac{135}{f(y)}}} \times 100% \\
= \frac{23.456S \times 10^{-3}}{Q} \%
\]

### Table 7. Results and errors of experiments

| Feeding amount/ (kg/s) | Monitor loss rate | Actual loss rate | The relative error |
|------------------------|------------------|------------------|--------------------|
| 7.0                    | 1.211            | 1.185            | 2.15               |
| 7.5                    | 1.427            | 1.393            | 2.38               |
| 8.0                    | 2.012            | 1.975            | 1.84               |
| 8.5                    | 2.331            | 2.272            | 2.53               |
| 9.0                    | 2.825            | 2.736            | 3.15               |

The formula of \( L \) is written into the program of cleaning loss monitoring system. The test method and wheat parameters used are the same as the above research on cleaning loss model. The relative error between the sensor monitoring value and the actual loss value under different feeding amounts is studied. The monitoring loss rate is measured by sensors and the actual loss rate is obtained by manual statistics. After the end of each group of tests, the grains harvested and the grains lost after cleaning and screening were weighed, and the actual loss rate was calculated. The sensor monitoring value was compared with the actual value, as shown in table 7.

The experimental results show that with the increase of system feed, the cleaning loss rate increases gradually, the relative error of sensor monitoring also increases, and the sensor monitoring value is larger than the actual value.

### 5. Conclusion

1. A cleaning loss monitoring system based on PVDF piezoelectric film and a grain threshing and cleaning test bench were developed to realize the online monitoring of the cleaning loss test bench of the wheat harvester. The test results showed that the relative error range of the monitoring system was 1.84% to 3.15%, fully meeting the loss monitoring of the wheat harvester.

2. The distribution law of cleaning loss caused by fan speed was studied, and the corresponding cleaning loss monitoring model was established, and that provided the decision-making basis for determining the optimal installation location of the sensor, for example, the optimal installation location of the test bench was 0.3m in longitudinal spacing with the cleaning screen and 0.7m in transverse spacing.

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