Development and optimization of a novel grain flow sensor based on PVDF piezoelectric film

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Abstract: A novel grain flow sensor consists of an impact plate and a PVDF (Polyvinylidene Fluoride) piezoelectric film was developed in this research. The kinetic model of the grain flow sensor was built to analyze the steady and transient vibration disturbances which had a significant influence on performance of the sensor, and the results showed that damping ratio of the sensor was the key factor to improve accuracy of the sensor. To maximize damping ratio of the sensor, the thickness of the impact plate and damping material were optimized according to a loss factor model of the free damping structure. The optimized results indicated the most appropriate thickness ratio of damping material and the impact plate was 6. A test rig equipped with the novel grain flow sensor and weight sensors which could simulate field situations was built to investigate the performance of the sensor, on which test experiments under different feed flows were conducted. The results showed that the maximum error of the sensor was 3.02% and the mean error was 2.15%, which revealed that the novel grain flow sensor could be used to measure grain flow. Comparing with conventional grain flow sensors, the novel grain flow sensor has the features of high accuracy, simple structure and flexible signal processing methods.

Keywords: grain flow sensor, vibrations, free damping structure, test rig
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1 Introduction

Grain flow sensor is the core part of yield monitoring system in precision agriculture. Impact-type[1], ray-type[2], volume-type[3] and weight-type[4] are common types of grain flow sensors. Due to the security and reliability, impact-type grain flow sensors are widely applied in yield monitoring system. These sensors usually measure the force of grain exerted on the impact plate which usually at the exit of the clean grain elevator. The grain flow is proportional to the measured force of grain.

The conventional impact-type grain flow sensors use strain gauges as force sensing elements, which are susceptible to interference of vibrations from a rice-type combine. To reduce vibrations, the researchers have done a lot of researches. Chosa and Kobayashi[5] developed a dual-plates differential impact-based grain flow sensor which consisted of a measuring plate and a reference plate, the measuring plate received impact of the grain flow, and the reference plate sensed vibrations. A differential method was used to reduce vibrations. Hu et al.[6] used the same method with Chosa. Wei et al.[1] also developed a dual-plates differential impact-based

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grain flow sensor. But the differential signal was obtained in frequent domain to improve measuring accuracy and stability of the sensor. Li et al.[7] proposed a regression differential method for a dual-plates differential impact-based grain flow sensor. Field test results showed that the regression difference method was superior to the direct differential method in eliminating vibration. Qiu et al.[8] used contacts model to simulate the impact action between the rice particles flow and the impact plate in order to improve the measuring accuracy of grain flow. Zhou et al.[9] designed an impact-type mass flow sensor using a parallel-beam load cell to measure the impact force caused by change in momentum of grain flow. In order to overcome vibration disturbance of the sensor frame, both the structure and the mechanical damping of the load cell were optimized[10], and the output signal of the sensor was processed by an adaptive filter[11].

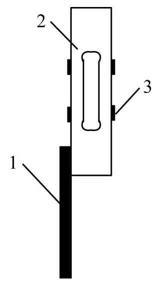
In addition to strain gauge, the piezoelectric ceramics have also been used as force sensing element of grain flow sensor. Wang et al.[12] developed a grain flow sensor based on the piezoelectric ceramics. Testing results showed the measuring errors of the sensor were within 5%. Gao et al.[13,14] used a redundant piezoelectric ceramics as a vibration sensor to compensate the impact of vibrations. Both indoor and field test results indicate that this sensor was of high precision.

The conventional impact-type grain flow sensor needs elastic elements to transmit the force of grain. Vibrations result in large deformation of elastic elements and distortion of signals from force sensing elements. Thereby the force of grain is not proportional to the grain flow. PVDF piezoelectric film is a novel polymer piezoelectric material which has a little response to structure vibrations and works without elastic elements to transmit forces as force sensing element. In light of the above advantages, a novel grain flow sensor based on PVDF piezoelectric film was developed in this research. The novel grain flow sensor is different from the conventional impact-type grain flow sensors and consists of PVDF piezoelectric film and impact plate. PVDF piezoelectric film, whose piezoelectric effect is used to measure the force of grain, plays a double role of elastic element and force sensing element in the novel grain flow sensor.

2 Structural design

2.1 Structure of the novel sensor

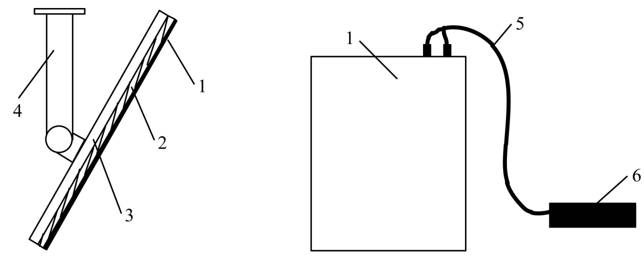
The conventional impact-type grain flow sensor is shown in Figure 1. Its structure determines that it is easily interfered by vibrations.



1. Impact plate 2. Elastic element 3. Force sensing element.

Figure 1 Structure of conventional impact-based grain flow sensor

The structure of novel sensor developed in this research is shown in Figure 2. The sensor consists of six components, including a PVDF piezoelectric film, a damping material, an impact plate, a fixed mount, a shielded wire and a charge amplifier. The PVDF piezoelectric film is accessed to the charge amplifier through the shielded wire. The PVDF piezoelectric film is stuck on the side of the impact plate, and the fixed mount is on the other side of the impact plate. The PVDF piezoelectric film is installed at the exit of combines by a fixed mount that adjust the novel sensor's installation angle and height. The damping material is laid between the PVDF piezoelectric film and the impact plate. A free damping structure designed to covering a layer of damping material on one or two sides of vibrational structure was composed of the damping material and the impact plate. The damping material is called free damping layer. When bending vibration occurs, damping material vibrates together with the base structure. Then tension and compression deformation is generated inside the damping material, so that the damping material can transform mechanical energy into heat energy.



a. Mechanical structure b. Electrical structure

Note: 1. PVDF piezoelectric film; 2. Damping material; 3.Impact plate; 4. Fixed mount; 5. Shielded wire; 6. Charge amplifier.

Figure 2 Structure of novel grain flow sensor

2.2 Material selection

2.2.1 PVDF piezoelectric film

In 1969, Japanese researcher Kawai found that PVDF material had strong piezoelectric properties after polarization. Therefore, PVDF piezoelectric films are widely used in the area of stress measurement, nondestructive test and biomedical and so on[15,16]. So far, various kinds of PVDF piezoelectric film have been developed to meet different requirements. Piezoelectric properties of PVDF piezoelectric film perform are as follows: when the piezoelectric film deformed by external force, charge accumulation will appear on polarization plane. While the external force disappeared, piezoelectric film will resume uncharged state. Assuming that the polarization direction of the polarization is 3-axis, the other two directions perpendicular to the 3-axis are defined as 1-axis and 2-axis which are shown in Figure 3. Using PVDF piezoelectric film as force sensing element, the piezoelectric formula can be expressed as follows:

$$D_3=d_{31}T_1+d_{32}T_2+d_{33}T_3 \quad (1)$$

where, D_3 is electric displacement or charge density on the 3-axis, pc/m^2; d_{31}, d_{32} and d_{33} are piezoelectric constants of the 3rd polarization direction respectively on the 1-axis, 2-axis and 3-axis, pc/N; Subscript 33 represents that the polarization direction is same with the direction of external force. T_1, T_2 and T_3 are normal stress respectively on the 1-axis, 2-axis and 3-axis, Pa.

As can be seen from Equation (1), normal stress in three directions results in charge accumulation on the corresponding two sides of piezoelectric film. Therefore, stress in all directions is related to charge accumulation when PVDF piezoelectric film is stressed or bending. Considering that the size of PVDF piezoelectric film in the thickness direction is less than that of the other two directions, the stress exerted on PVDF piezoelectric film is in the direction of 3-axis only, which means that piezoelectric only constant d_{33} is effective and then Equation (1) can be simplified as:

$$D_3=d_{33}T_3 \quad (2)$$

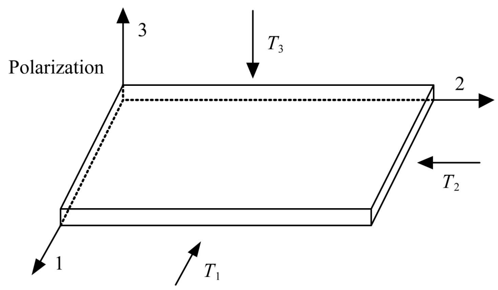


Figure 3 Polarization of the PVDF piezoelectric film

According to the size of the clean grain elevator's exit, a LCL2218 PVDF piezoelectric film is selected as force-sensitive element of the sensor with size 220 mm × 180 mm × 0.07 mm and piezoelectric constant d_{33} of 200 pc/N.

2.2.2 Damping material

Damping material can be divided into four categories: damping viscoelastic materials, including rubbers and plastics; damping alloys, including iron-based substrate or other non-ferrous metallic material; composite material, including laminated material and mixed material and coulomb friction damping material. According to the structural characteristics of the novel sensor, damping viscoelastic material, the specific choice of rubber, covers the surface of the impact plate. Rubber will change greatly with temperature. When Rubber is used as damping material, it must meet the follows conditions:

1) The peak of rubber loss factor η_{max} is high, and temperature corresponding to that peak and work temperature need to be consistent.

2) Work temperature range (η>0.7) should be as wide as possible.

3) Hard to aging and burning, easy to paste, good process performance.

The temperature range for the grain harvest is 4°C-20°C. Work temperature range for Rubber needs to be wider than that temperature range. So we choose ZN-1 rubber for normal temperature, the specific parameters of ZN-1 rubber are shown in Table 1.

Table 1 Specific parameters of ZN-1 rubber

Parameters	Values
Work temperature range (η>0.7)	−16°C-50°C
Peak of loss factor η_{max}	1.4-1.5
Temperature corresponding to peak of loss factor	13℃

2.2.3 Impact plate

Under vibrations and the force of grain, the impact plate of the novel sensor needs to have a certain hardness to resist fatigue deformation, and also needs to have a certain toughness to prevent brittle fracture. The common plate mainly includes stainless steel plate 304, aluminum plate 6063 and copper plate C2680. The mechanical properties of three plates are shown in Table 2.

Table 2 Mechanical property of three plates

Material	Hardness/HV	Impact toughness/J·cm^{-2}
Stainless steel plate 304	270-290	70-90
Aluminum plate 6063	70-75.6	10-20
Copper plate C2680	85-145	15-40

As can be seen from Table 2, hardness and impact toughness of stainless steel 304 are higher than the other two materials. And besides, it is easy to machining and welding. So considering the mechanical properties, processing and economy, stainless steel 304 is the best choice. In accordance with the specifications of thickness and strength conditions, the thickness of the stainless steel plate is 1 mm.

2.3 Principle of measurement

A new equation $D_3S=d_{33}T_3S$ is deduced from Equation (2). That is:

$$Q=d_{33}F \tag{3}$$

where, S is the area of the force of grain; Q is the total charge of PVDF piezoelectric film, C; F is the force of grain, N. Equation (3) shows that the total charge of PVDF piezoelectric film is proportional to the force of grain. Because internal impedance of PVDF piezoelectric film results in weak output signal, the measuring circuit for PVDF piezoelectric film often needs to be connected to a charge amplifier which has big input impedance, and then output signal of PVDF piezoelectric film can be amplified. So the equation (4) can be obtained:

$$U=\alpha Q \tag{4}$$

where, U is the output voltage of the charge amplifier, V; α is the charge amplification coefficient.

From Equations (3) and (4), the force of grain can be expressed as:

$$F=\frac{U}{\alpha d_{33}} \tag{5}$$

According to the measurement principle of impact-type grain flow sensors[17], grain flow is expressed as:

$$q=\frac{m_t}{t_1-t_2}=\frac{\bar{F}}{\Delta v} \tag{6}$$

where, q is the grain flow during t_1−t_2, kg/s; m_t is the total grain mass during t_1−t_2, kg; $\bar{F}$ is the mean force of grain during t_1−t_2, N; Δv is the speed difference before and after grain exerted on the impact plate. If a constant speed difference can be generated in the grain flow, then there a direct relationship between the mean force of grain and the grain flow can be got. A constant speed difference can be produced if grain hit impact plate with the same speed and direction. For simplify, Δv is set to be a constant, m/s; t_1−t_2 can be set according to sampling time of yield monitor system, s.

3 Structure optimization of the novel sensor

3.1 Kinetic model of the novel sensor

The novel sensor can be simplified as a single degree of freedom spring damping model shown in Figure 4. The kinetic model of the sensor can be expressed as follows:

$$m\ddot{x}+c\dot{x}+kx=f(t)+r(t) \tag{7}$$

where, $f(t)$ is the force of grain; $r(t)$ is the vibrations; m is the novel sensor mass; k is the stiffness coefficient of the novel sensor mass; c is the damping coefficient; x is the displacement of the novel sensor.

Bending deformation of the novel sensor interferes with the measurement of grain flow. The vibrations and the force of grain both create the novel sensor bending deformation. So interferences can be divided into two types: steady interference and transient interference. Next we will analyze the key factors which can suppress interference by kinetic model.

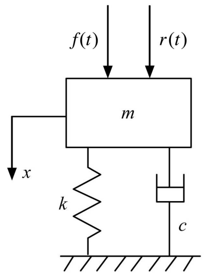


Figure 4 Kinetic model of the novel sensor

3.2 Steady interference analysis

Regardless of the impact of grain, and then Equation (7) can be simplified as:

$$m\ddot{x} + c\dot{x} + kx = r(t) \quad (8)$$

When the system with damping is subject to harmonic excitation force, vibration is a simple harmonic motion. The frequency of vibration is the same with excitation frequency, while amplitude and phase angle of vibration depend on the system itself. If $r(t)=a\sin\omega t$, steady-state response of the novel sensor to $r(t)$ can be described by:

$$x = A\sin(\omega t - \varphi) \quad (9)$$

where,

$$A = \frac{a}{\sqrt{(1-\lambda^2)^2 + (2\xi\lambda)^2}} \quad (10)$$

$$\varphi = arctg\frac{2\xi\lambda}{1-\lambda^2} \quad (11)$$

$$\lambda = \frac{\omega}{\omega_n} \quad (12)$$

$$\omega_n = \sqrt{\frac{k}{m}} \quad (13)$$

$$\xi = \frac{c}{2\sqrt{km}} \quad (14)$$

where, A is the amplitude; φ is the phase angle; ω is the excitation frequency; a is the excitation amplitude; λ is the frequency ratio; ω_n is the natural frequency of the novel sensor; ξ is the damping ratio.

Vibrations are the steady interference for measurement of grain flow. With amplitude ratio A/a as y-coordinate and frequency ratio λ as x-coordinate, Figure 5 shows the amplitude-frequency response curves of the novel sensor under different damping ratio ξ. As is shown in Figure 5, when the vibrations frequency is close to natural frequency of the novel sensor, the novel sensor resonates because damping ratio is small. Larger bending deformation of the novel sensor will occur due to resonation. According to Equation (1), the output charge from PVDF piezoelectric film is related to the stress on the three directions. Hence bending deformation of the novel sensor will lead to a big measurement error. Vibration frequency changes with different work conditions, so it is likely to be close to the natural frequency of the novel sensor. However, when the damping ratio is large, even though vibration frequency is close to the natural frequency of the sensor, amplitude of resonance peak is very small. In another word, bending deformation of the novel sensor is restrained.

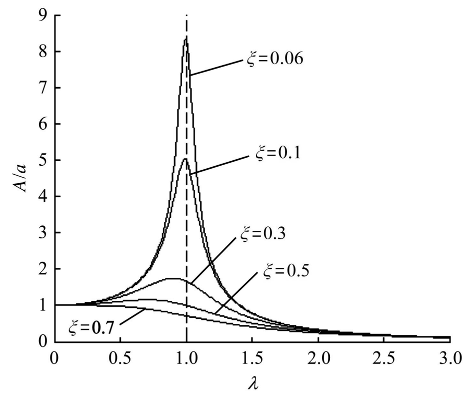


Figure 5 Vibration amplitude-frequency response curve of the novel sensor under different damping ratio

3.3 Transient interference analysis

If vibrations are not taken into consideration, the novel sensor will work only under the action of the force of grain, and then Equation (7) can be simplified as:

$$m\ddot{x} + c\dot{x} + kx = f(t) \quad (15)$$

With the assumption that action time is very short, the force of grain can be described by unit impulse function. The response of the novel sensor to unit function can be converted into free vibration with initial condition $x_0 = 0,\ \dot{x}_0 = 1/m$:

$$x(t) = \frac{1}{\mathrm{m}\omega_n\sqrt{1-\xi^2}} e^{-\xi\omega_{\mathrm{n}}t}\sin(\sqrt{1-\xi^2}\,\omega_{\mathrm{n}}t) \quad (16)$$

Equation (16) indicates that the force of grain lead to the exponential decay of transient amplitude. Decaying rate of transient amplitude depends on damping ratio of the novel sensor. When damping ratio of the novel sensor is smaller, transient amplitude decays slower; when damping ratio of the novel sensor is larger, transient amplitude decays faster. Damping ratio of the novel sensor is very small (0.01-0.02), because the novel sensor is made of stainless steel 304. So its transient amplitude decays slower, which is regarded as a transient interference that impacting on sampling time and measuring accuracy of the novel sensor. Especially when damping ratio of the novel sensor is closed to zero, Equation (16) becomes:

$$x(t)=\frac{1}{\mathrm{m}\omega_{\mathrm{n}}}\sin\omega_{\mathrm{n}}t \tag{17}$$

Equation (17) is a sinusoid, which indicates that if the damping ratio of the novel sensor is minimal, the novel sensor does not have good dynamic characteristics. Figure 6 shows the response of the sensor to unit impulse function under different damping ratio.

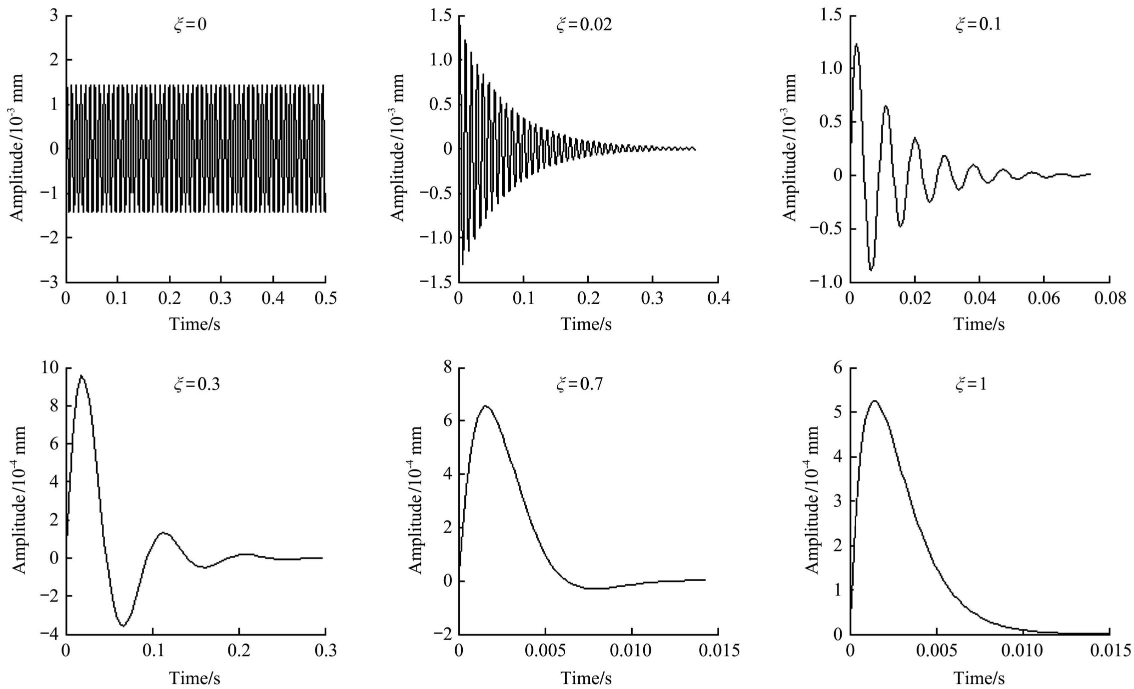


Figure 6 Impulse response of the novel sensor under different damping ratio

Above all, the damping ratio of the novel sensor is crucial to improve measuring accuracy. Increasing of the damping ratio of the novel sensor not only suppresses steady interference, but also reduces transient interference.

3.4 Structure optimization

Damping material is helpful to raise the damping ratio of the novel sensor. After free damping treatment of the novel sensor, the damping ratio of the novel sensor is equivalent to the damping ratio of free damping structure. According to principle of deformation energy, loss factor of free damping structure is shown as follows:

$$\eta=\beta\cdot\frac{\mu h(3+6h+4h^2)}{1+\mu h(5+6h+4h^2)} \tag{18}$$

where, η is the loss factor of free damping structure; β is the loss factor of damping material; μ is young modulus ratio of damping material and the impact plate; h is the thickness ratio of damping material and the impact plate.

In the case of small damping, the damping ratio of free damping structure is 0.5 times of loss factor approximately[18], that is

$$\xi=\frac{\beta}{2}\cdot\frac{\mu h(3+6h+4h^2)}{1+\mu h(5+6h+4h^2)} \tag{19}$$

According to Equation (19), relationship curves of $2\xi/\beta$ and h, μ can be drawn and are shown in Figure 7. The larger the μ, the faster $2\xi/\beta$ rises rapidly with the increase of h. When μ is constant, the $2\xi/\beta$ rises with the increase of h. However, when h is over a certain value, $2\xi/\beta$ reaches the limit.

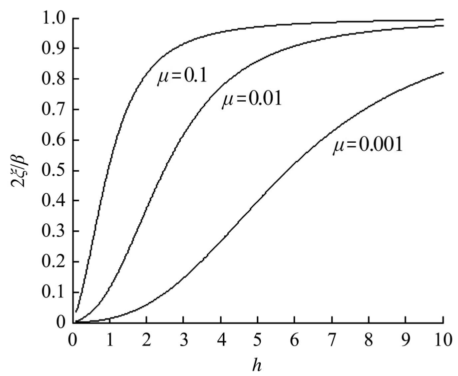


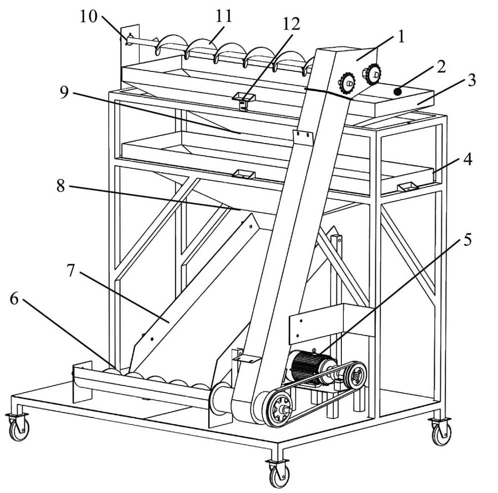
Figure 7 Relationships between $2\xi/\beta$ and h, μ

In the case of μ is constant, ξ can obtain optimum value with appropriate h. For the novel sensor, according to the 1.3 section, the optimal parameters are: μ=0.08, h=6, ξ=0.348.

4 Test and discussion

4.1 Test rig

A sensor test rig for grain flow was built to measure the accuracy of the novel sensor. The components of the test rig are shown in Figure 8. The clean grain elevator was obtained from CF806 combine with size of 2.3 m × 0.255 m × 0.16 m[25]. The elevator was driven by a 3 kW induction motor. The rated speed of the elevator was 331 r/min. The weighting bin and storage bin were capable of holding approximately 0.27 m^3 of grain. The 200 mm wide valve plate at the bottom of the storage bin allowed grain flowing from the storage bin into the sideway. The slope of the sideway was more than 36° which made grain dropped rapidly. The supply auger conveyed grain from the sideway to the clean grain elevator.



1. Clean grain elevator 2. Humidity sensor 3. Weighting bin 4. Storage bin 5. Induction motor 6. Supply auger 7. Sideway 8. Valve plate 9. Baffle plate 10. Speed sensor 11. Conveying auger 12. Weighting sensor

Figure 8 Schematic diagram of the test rig for grain flow sensor

The test rig transferred grain from the storage bin to the clean grain elevator and then to the weighting bin. The weighting bin was installed on three weighting sensors which measured the actual weight of the grain. The weighting bin and three weighting sensors would be regarded as the reference. The feed flow could be controlled by adjusting opening of the valve plate manually.

The data acquisition system was used to collect the grain flow and accumulated grain mass in the weighting bin. The primary components of the data acquisition system were an acquisition card, a laptop and Labview software. The acquisition card was NI USB-6216 with 16 analog inputs[20]. The software Labview provided the user interface of the data acquisition and data storage.

4.2 Test process

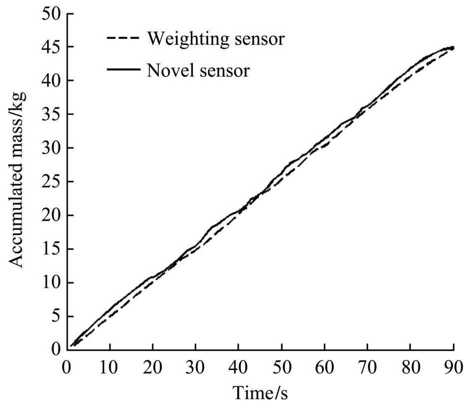
Paddy rice was chosen for the test as test sample, because the CF806 was a paddy rice-type combine. First, clean grain elevator worked at rated speed though controlling frequency of the induction motor. And then the feed flows of 0.5 kg/s, 1.2 kg/s, 2 kg/s were achieved with valve plate. The feed flow stabilized after about 7 s and data logging started. Each test, along with each feed flow being repeated three times, lasted about 90 s. In this research, measurements from three weighting sensors were considered as true values. The term “error” means the percent difference of the measured quantities between the novel flow sensor and three weighting sensors. After pre-processing by the EMD (Empirical mode decomposition), all data were used for error statistics.

4.3 Results and discussion

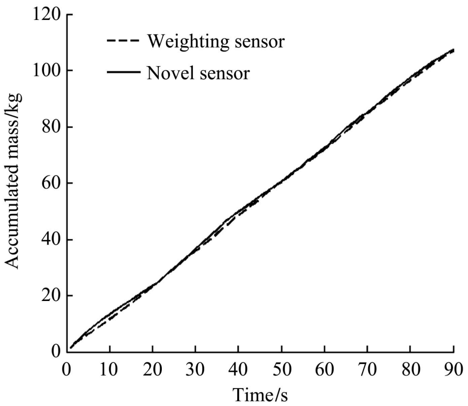
The accuracy of the mass flow sensor as shown in Figure 9 was very high when measuring accumulated grain mass. Error statistics of the novel sensor error for accumulated mass are shown in Table 3. The mean error of the novel sensor in measuring accumulated grain mass was 2.15% and the maximum error was 3.02% at 0.5 kg/s feed flow. However, it should be pointed out that the low feed flow resulted in a great error[19,20]. Overall, the accumulated accuracy of the novel sensor was very good.

Table 4 shows the comparison of the novel sensor with other two sensors that were developed in recent years.

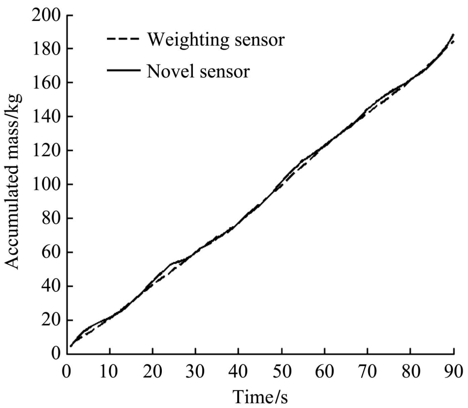
Accuracy of the novel sensor is better than the other two sensors (Table 4). Accuracy of impact-type grain flow sensors was improved because PVDF piezoelectric film was chosen as the force sensing element. The novel sensor is better than the conventional impact-type grain flow sensors not only in accuracy but also in structure design and signal process method.



a. At 0.5 kg/s feed flow



b. At 1.2 kg/s feed flow



c. At 2 kg/s feed flow

Figure 9 Accumulated mass curves of sensor at different feed flow

Table 3 Error statistics of the novel sensor

Feed flow (number)/kg·s^{-1}	Maximum error/%	Mean error/%
0.5(1)	3.01	2.57
0.5(2)	2.96	2.25
0.5(3)	3.02	2.42
1.2(1)	2.81	2.01
1.2(2)	2.96	2.04
1.2(3)	2.91	2.19
2(1)	2.72	2.11
2(2)	2.86	1.98
2(3)	2.94	1.74
mean		2.15

Table 4 Comparison of accuracy for different sensors

	Maximum error/%	Mean error/%
Single impact plate[12, 21, 22]	5.28-6.82	4.10-4.43
Dual impact plate [1, 23, 24]	3.10-3.58	2.17-2.23
The novel sensor	3.02	2.15

Structure design: the novel sensor consists of PVDF piezoelectric film and the impact plate without structure design problems that the conventional impact-type grain flow sensors facing. Piezoelectric materials are made into different thickness and shapes films due to their flexibility and processing. Therefore, the design work is just the dimensions of PVDF piezoelectric film and the impact plate according to dimensions of outlet of clean grain elevator.

Signal process method: PVDF piezoelectric film has a little response to structure vibrations and more importantly it works without elastic elements which are used to transmit forces as force sensing element, furthermore, damping material can effectively suppress vibrations. So signal process method for the novel sensor is mainly used to remove high frequency random noise. There are many methods to remove high frequency random noise, such as EMD, Wavelet and mean filtering and so on. As a result, signal process methods used in the novel sensor are multiple and the selection is more flexible.

5 Conclusions

A novel impact-type grain flow sensor was developed based on PVDF piezoelectric film. The novel sensor is different from the conventional impact-type grain flow sensors, which consists of PVDF piezoelectric film and the impact plate. The structure of the novel sensor is simple and unique because PVDF piezoelectric film is both elastic element and force sensing element. The novel sensor is high sensitivity, good linearity, and flexible to apply signal process methods.

A kinetic model of the novel sensor was built, which showed that the damping ratio of the novel sensor was the key to suppress interferences and improve the accuracy. The thickness of damping material and the impact plate were optimized according to the principle of deformation energy, and the optimum damping ratio of the novel sensor was obtained.

A test for accuracy of the novel sensor was carried out on a test rig. Results showed the mean error of the novel sensor when measuring accumulated grain mass was 2.15% and the maximum error was 3.02% at 0.5 kg/s feed flow. Accuracy of the novel sensor was better than the conventional impact-type grain flow sensors. The novel sensor is a new way for the measurement of grain flow.

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