Sensor for monitoring rice grain sieve losses in combine harvesters

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Grain sieve losses are important parameters to judge the performance of cleaning shoes in combine harvesters. To keep grain sieve loss within acceptable limits, an impact-type piezoelectric sensor was developed for real-time monitoring. Rice grain and short straw particle models were established according to their physical properties, and discrete element method (DEM) simulations were carried out to understand their collision behaviour with the sensor. The influence of grain shape, straw length and impact angle on variations of the maximum normal contact force and force rise-time were analysed in detail. Differences in normal collision force, and force rise-time occurred which lead to corresponding differences in signal frequency and voltage amplitude. A signal processing circuit, which mainly consisted of a band-pass filter circuit and a voltage comparator circuit, was designed to discriminate for full grains. Field tests results indicated that measurement errors recorded by the sensor and checked against manually measurements were <4.48%.

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1. Introduction

Combine harvesters operate all over the world, harvesting different crops under different environmental conditions. They have functions which cover the entire harvesting process that can be divided into cutting, threshing, separating, cleaning and storing. Cleaning process, refer to the final separation of grain from material other than grain (MOG), which is influenced by a wide range of parameters including crop yield, climate, threshing and cleaning settings (Craessaerts, De Baerdemaeker, Missotten, & Saeys, 2010; Craessaerts, Saeys, Missotten, & Baerdemaeker, 2010). Grain sieve loss, which is influenced by a wide range of parameters such as design, operating conditions as well as crop properties, is an important parameter to judge the performance of the cleaning shoe. In China, evaluation of grain sieve losses mainly relies on manual labour, using a canvas to collect all mixed material at the exhaust port, then filtering out the grains from MOG by a re-cleaner, weighing them and then calculating the absolute sieve loss. This value can be used for benchmarking, but it cannot be used for system control because it cannot be obtained real-time. With the advances in sensors and automation in recent years, researchers have proposed many sensors for use with combine harvesters to extract real-time information from the working process (Craessaerts, Saeys, Missotten & De Baerdemaeker, 2008; Omid, Lashgari, & Mobli, 2010; Reyns, Missotten, Ramon, & Baerdemaeker,
2002), either by monitoring machine settings (e.g. driving speed, fan speed, upper and lower sieve opening) (Mcgechan, 1982), machine load (e.g. feed-rate, torque drum, engine load and grain mass flow) (Loghavi, Ehsani, 2002), or by measuring field-related parameters (e.g. moisture content of grain, machine lateral and longitudinal inclination) (Craessaerts, De Baerdemaeker, et al., 2010; Craessaerts, Saeys, 2004). Some researchers have also engaged in grain sieve loss auto-detection technology (Hiregoudar, Udhaykumar, Ramappa, Shreshta, & Medaet, 2011) and many advanced combine harvesters have grain sieve loss monitoring sensors installed (Eldredge, 1985; Liu and Leonard, 1993; Zhou, Zhang, Liu, & Yuan, 2010; Gao, Zhang, Yu, & Li, 2011; Li, 2006; Ni, Mao, & Tian, 2011; Osselaere, 1985). To date, a measure was found for monitoring grain loss by quantifying grain impacts during a fixed interval based on piezoelectric effect. However, the combine harvesters produced in Europe and North America are mainly used for harvesting crops, such as wheat, bean and oil-seed rape. Rice, one of the most important crops in China, is very different in its physical properties to these crops and there is therefore a need to develop a signal processing circuit to accurately discriminate rice grain loss from MOG.

The surface of grain sieve loss monitoring sensors usually consists of a rigid plate. Different materials collide with the plate causing differences in the frequency and force of the collision. The impact behaviour of grains and MOGs with the plate is therefore a critical step for designing a signal processing circuit for real-time monitoring. In recent years,
collisions between deformable objects has been the subject of intensive investigation by many researchers using theoretical, numerical, and experimental methods (Sommerfeld, 2002; Wynn, 2009; Vu-Quoc & Zhang, 1999; Zhang & Vu-Quoc, 2002). Proper discussion and understanding of the phenomena involved cannot be obtained without the help of numerical simulations. Numerical simulations based on the discrete element method (DEM) (Cundall & Strack, 1979) have shown to be very useful in understanding the involved phenomena for numerous applications (Bertrand, Leclaire, & Levecque, 2005; Li, Li, Gao, Zhao, & Xu, 2012; Sakaguchi, Suzuki, & Favier, 2001). However, previous research has mainly focussed on creating a deep insight into certain aspects of grain particle impacts with the plate. Studies have mainly used sphere models as discrete units, which sometimes vary greatly with the real materials, and result in certain calculation errors occurring (Wojtkowski, Pecen, Horabik, & Molenda, 2010; Wynn, 2009). Also, materials impacting on the sensor are complex because, in addition to grain particles, there are also MOG have a strong influence on monitoring accuracy. Although a number of research papers are available describing the interaction of wheat grains with machine components by means of DEM, no literature is available that discusses the collision behaviour of rice and its MOG using a rigid plate (Gao et al., 2011; Wojtkowski et al., 2010).

In this paper, the design of a grain sieve loss monitoring sensor using YT-5L piezoelectric ceramics as sensing element, and utilising DEM to simulate the collision behaviour of rice grain and its MOG. The influence of grain shape, straw length and collision angle on variations of the normal contact force and force rise-time are analysed in detail laying the foundation for designing a circuit to accurately discriminate rice grain in real-time. A grain sieve loss monitor mathematical model was developed and field tests carried out.

2. Materials and methods

2.1. Structure of the sensor

Due to the small mass of rice grains, the grain collision signal is relatively weak so a grain loss monitoring sensor was developed by selecting a YT-5L piezoelectric ceramic as a sensitive element and pasting it into the centre of the sensitive plate of a sensor. YT-5L piezoelectric ceramics (produced by Baoding Sky Ultrasonic Technology Co., Ltd., Baoding, China, and with a piezoelectric constant was 450 pc N\(^{-1}\)) have high sensitivity to dimensional changes and are able to respond to micro-vibrations. They are especially suited for measuring dynamic changes (Song, Gu, Mo, Hsu, & Dhonde, 2007; Wang, Wang, & Wang, 2009). The sensitive plate was constructed from stainless steel 304 and was 550 mm (length) $\times$ 125 mm (width) $\times$ 1.5 mm (thickness). Four rubber shock absorbers installed within the sensitive plate supported the support plate and the rack connection parts to eliminate vibrational interference (Pan, Shangguan, Chai, & Huang, 2009; Sculli & Inman, 1998). The installation angle of the sensor was adjustable in the range of 0–60° to prevent output materials accumulating on the sensor surface. The designed grain sieve loss monitoring sensor is shown in Fig. 1 and the properties of the YT-5 piezoelectric ceramic are shown in Table 1.

The feeding quantity of the combine harvester used in work was about 4.5 kg s\(^{-1}\), the output grains which fell onto the sieve at about 1.5 kg s\(^{-1}\), which gave the ratio of grain to MOG of about 2 for rice. According to national standards for combine harvesters in China, the grain sieve loss ratio should be no larger than 1%, so grain sieve losses are about 15 g s\(^{-1}\) or about 500 grains s\(^{-1}\) assuming the thousand-grain weight is 30 g. The averaged values of proportional relationships between grain total sieve losses and grains in the sensor monitoring area were about 0.12, thus the detecting frequency of the sensor should >60 grains s\(^{-1}\).

Transmit collision signals have a rapid decay in the plane of symmetry of the sensitive plate and the system has a strong vibration resonance because of its low damping ratio. This transform the input signal into a harmonic oscillation signal which is an energy signal, and this attenuates with time affecting the detecting frequency. The shorter the attenuation time, the more rapidly the vibration system achieves a steady-state status, and sensitivity of the system increases. Therefore, selecting an appropriate damping ratio was the basis of detecting a signal with a short attenuation time. Viscoelastic damping layers integrated into structures have been widely used in engineering to suppress the transmission of vibration and noise to structures (Liu, Hua, & Zhang, 2004; Nakra, 1998). To accelerate the detection speed of the monitor, a partially constrained viscoelastic damping layer treatment was applied to the surface of the sensor. Optimal position of the damping

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**Table 1 – Properties of YT-5 piezoelectric ceramic material.**

<table>
<thead>
<tr>
<th>Description</th>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electromechanical coupling coefficient</td>
<td>$K_{33}$</td>
<td>0.71</td>
</tr>
<tr>
<td>Piezoelectric constant PC/N</td>
<td>$d_{31}$</td>
<td>270</td>
</tr>
<tr>
<td></td>
<td>$d_{33}$</td>
<td>550</td>
</tr>
<tr>
<td>Relative permittivity $\varepsilon$</td>
<td>$T_{33}$</td>
<td>7.0</td>
</tr>
<tr>
<td>Curie temperature/C</td>
<td>$T_c$</td>
<td>280</td>
</tr>
<tr>
<td>Mechanical quality factor</td>
<td>$Q_m$</td>
<td>70</td>
</tr>
<tr>
<td>Density g ml(^{-1})</td>
<td>$\rho_m$</td>
<td>7.6</td>
</tr>
</tbody>
</table>
layer laying and collision signal waveform shown in Fig. 2. Figure 2(b) shows that attenuation time was of the order of 2–3 ms, which indicated that the sensor could in theory identify more than 300–500 grains s\(^{-1}\) and therefore meet the required specification.

Since rice grains and its MOG have different Young’s modulus, coefficient of restitution for the sensitive plate and mass, the maximum normal overlap \(a_{\text{max}}\) and collision time \(t_r\) displayed significant differences according to conservation of energy principle, where \(a_{\text{max}}\) and \(t_r\) can be deduced by:

\[
a_{\text{max}} = \left(\frac{15}{16} \frac{m v_n^2}{E^* R^*} \right)^{2/5}
\]

\[
t_r = 2.94 a_{\text{max}} / v_n
\]

Where, \(v_n\) is vertical collision velocity, \(E^*\), \(R^*\) is given by:

\[
E^* = \left[ \frac{1 - v_1^2}{E_1} + \frac{1 - v_2^2}{E_2} \right]^{-1}
\]

\[
R^* = \frac{1}{R_1} + \frac{1}{R_2}
\]

where \(v_1\) and \(v_2\) are the Poisson’s ratio of the two materials; \(R_1\) and \(R_2\) are the radius of the two elements, \(E_1, E_2\) are the Young’s modulus of elasticity.

Due to piezoelectric properties and the polarisation direction of piezoelectric ceramics, the value of collision output voltage \(V_{\text{out}}\) was proportional to \(F_{n_{\text{max}}}\). The value of \(F_{n_{\text{max}}}\) was proportional to the maximum normal overlap \(a_{\text{max}}\), which meant that the larger \(a_{\text{max}}\) in sensitive plates, the larger \(F_{n_{\text{max}}}\). From Eq. (2) it can be seen that there were also great differences in rise time with different \(a_{\text{max}}\). Variations in normal collision forces, shown in Fig. 3, indicate that rise time \(t_r\) was equal to a quarter of the signal period. Differences in \(F_{n_{\text{max}}}\) and \(t_r\) produced corresponding differences in signal frequency and voltage amplitude, thus understanding \(F_{n_{\text{max}}}\) and \(t_r\) was a critical step in discriminating grains from MOG.

3. Discrete element method simulation mathematical model

From Section 2 it can be seen that rice grains fall in the harvester at frequency of about 60 grains s\(^{-1}\), hence the theoretical time interval between collisions was about 1/60 s. Experimental results showed that collision signals can be attenuated completely in around 1/60 s after the impact surface was treated with a partial constrained viscoelastic damping layer. Therefore, the main task was to design a circuit to discriminate between each grain collision. Therefore, the distribution of voltage amplitudes and rise times for each collision signal needed to be discriminated. Although the impact forces and force rise time for rice grain and short straw could have been measured experimentally, it is hard to obtain comprehensive information due to random nature of the collision attitude. DEM is a numerical technique that can model the motion of an assembly of particles which interact with each other through collisions.

3.1. Equations of motion

At each time step, the trajectory of each particle in a system can be obtained using a numerical time integration scheme and all forces acting on the particles, such as contact and body forces, are summed and can be described by Newton’s second law of motion. In the inertial coordinate, the governing
equations for the acceleration of the particle’s centre and the particle’s angular momentum can be written as:

$$m \frac{d^2 \mathbf{v}}{dt^2} = F_n + F_t + m \mathbf{g}$$  \hspace{1cm} (5)$$

$$I \frac{d^2 \mathbf{w}}{dt^2} = R \mathbf{U} \times (F_n + F_t)$$  \hspace{1cm} (6)$$

where \( m \) is the particle mass, \( \mathbf{v} \) and \( \omega \) are translational and rotational velocities of the particle, \( F_n \) and \( F_t \) are normal and the tangential impact forces, \( R \) and \( \mathbf{U} \) are rotating radius and the unit vector of rotating shaft, \( g \) is the gravitational acceleration, \( I \) is the moment of inertia. Therefore, the translational velocity \( \mathbf{v}_c \) of contact point in the plate can be deduced:

$$\mathbf{v}_c = \mathbf{v} + R \cdot \mathbf{U} \times \omega$$  \hspace{1cm} (7)$$

### 3.2. Normal contact model

In the DEM, particle positions and velocities for every time step are obtained from a step-by-step integration of the equations of motion. In this procedure, the evaluation of particle–particle interaction (i.e., contact) forces plays a critical role. Since particle–particle contact forces are calculated using force-displacement models, the accuracy and correctness of simulation results are highly dependent on the normal force-displacement and the tangential force-displacement models employed. The contact pressure during loading is less than the limiting contact pressure, the grain contact is treated as elastic. The Hertz-Mindlin (no slip) model provides relative velocity-dependent rolling friction and ensures the same torque being applied to each of the particles in contact. In this paper we choose this contact model, which can be considered as a ‘spring-dashpot’ configuration, to calculate the force changing process of grains and straws. During the elastic mode of loading for two contact spheres, the contact is treated as elastic and was governed by the Hertz formula, the normal contact force \( F_n \) which can be expressed by:

$$F_n = \frac{4}{3} E' R'^{1/2} \delta_n^{3/2}$$  \hspace{1cm} (8)$$

where, \( \delta_n \) is the normal overlaps.

The radius of the contact area between two spheres is given by:

$$a = \left( \frac{3PR'}{4E'} \right)^{1/3} = \sqrt{R'} \delta_n$$  \hspace{1cm} (9)$$

The pressure distribution over the contact area is then:

$$p(r) = \frac{3F_n}{2\pi a^2} \left[ 1 - \left( \frac{r}{a} \right)^2 \right]^{1/2}$$  \hspace{1cm} (10)$$

where \( r \) is the radius of the collision material.

If the contact pressure during the loading is less than the yield pressure \( p_y \), for a given value of \( p_y \), the radius of the contact area \( a_y \), corresponding to yield initiation at the centre of the contact area \( p_{y=0} = \sigma_y \) can be determined by:

$$a_y = \frac{\sqrt{\pi' p_y}}{2E'}$$  \hspace{1cm} (11)$$

The corresponding yield overlap is:

$$\delta_y = \frac{\pi^{2/3} R'^2}{2E'^{5/3}}$$  \hspace{1cm} (12)$$

### 3.3. Tangential contact model

The theory of Mindlin was used for the elastic frictional contact between two spheres in the tangential direction. Let \( F_n \) and \( F_t \) be the tangential contact forces before and after an increment of tangential displacement \( \Delta \delta \). The relationship between \( F_t \) and \( F_t^{(n+1)} \) is given by the following incremental formula:

$$F_t^{(n+1)} = 8aN'K_t \Delta \delta + F_t^{(n)}$$  \hspace{1cm} (13)$$

where \( K_t \) is computed according to Mindlin and Deresiewicz (1953), and the effective shear modulus \( G^* \) can be calculated by:

$$G^* = \frac{2 - v_1}{G_1} + \frac{2 - v_2}{G_2}$$  \hspace{1cm} (14)$$

where, \( G_1 \) and \( G_2 \) are the shear modulus of the two materials. Additionally, there are normal damping force \( F_d \) and tangential damping force \( F_t^* \) which can be written as:

$$F_d = 2 \sqrt{\frac{5}{8} \pi \rho \epsilon \rho'} \frac{m^* \nu_{rel}^2}{S_{nm}}$$  \hspace{1cm} (15)$$

$$F_t^* = 2 \sqrt{\frac{5}{8} \pi \rho \epsilon \rho'} \frac{m^* \nu_{rel}^2}{S_{nm}}$$  \hspace{1cm} (16)$$

where, \( \nu_{rel} \) is the normal relative velocity, \( \nu_{rel}^t \) is the tangential relative velocity, \( m^* \) is the equivalent mass, \( m^*, S_{nm}, S', \beta \) can be deduced by:

$$m^* = \frac{1}{m_1} + \frac{1}{m_2}$$  \hspace{1cm} (17)$$

$$S_{nm} = 2E' \sqrt{\rho \rho'}$$  \hspace{1cm} (18)$$

$$S' = 8G' \sqrt{\rho \rho'}$$  \hspace{1cm} (19)$$

$$\beta = \frac{\ln e}{\sqrt{\ln^2 e + \pi^2}}$$  \hspace{1cm} (20)$$

where \( m_1 \) and \( m_2 \) are the mass of the two elements, \( \rho \) is the contact radii, \( e \) is the coefficient of restitution.

### 4. Discrete element method simulations

#### 4.1. Particle models

The main ingredients of the cleaning shoe were rice grain (radius ratio generally 1–3 (Xu & Li, 2009)), long grass (100–300 mm in length), short straw (30–90 mm in length), and some light debris. An image of the main ingredients and their proportions is shown in Fig. 4. The physical figures of the grain and MOG are shown in Fig. 5.

Collision experiments indicated that blighted grains and light miscellaneous material have only a slight influence on the monitoring accuracy of the sensor since their masses were
relatively small. Therefore, modelling mainly focused on the collision process of rice grains and short straws impacting the plate. A commercial DEM code (EDEM® 2.5, DEM Solutions Ltd., Edinburgh, UK) was used in this work. The focus was on how results from the simulations could be used to optimise sensor design. Ellipsoid grain particles and short straw particles were simulated using composite particles made up of several overlapping spheres. This made it feasible to simulate the impact plate experiments within a reasonable period. Developed examples of grain particle model and short straw particle models are shown in Fig. 6. The diameter of the short straw was 5 mm. A cross section of the established short straw model shown in Fig. 6(b). Since straw has a hollow structure, 12 sphere particles of diameter 1 mm were used to make a circle ring, in each layer one sphere particle was tangential with the other. The distance between sphere centres in the two layers along the long axis was 0.8 mm. The sensitive plate was developed directly in the software with its thickness, size, physical properties (including deformation) defined according to the EDEM user guide. Rice grains and short straws were
simulated as colliding with the sensor surface with a vertical velocity of 2.5 m s\(^{-1}\); the time step for the simulations was \(5 \times 10^{-7} \) s. The mechanical properties of grains are strongly influenced by the moisture content, which plays a role similar to that of temperature for thermoplastics and metals. To better simulate the variation of the collision force, the parameters used in the DEM simulation were the mean values from the replicated tests measured in the laboratory. The laboratory tests were all carried out with fresh rice collected in the field using a texture analyser (TA.new plus, Isenso, Washington, D.C, USA) and suitable values obtained from the literature (Li et al., 2008; Qiao, 1992; Yang, Yang, & Li, 2009; Zhang, Li, & Yang, 2006). The parameters used in the DEM simulations were shown in Table 2.

### Table 2 – Summary of DEM simulation parameters.

<table>
<thead>
<tr>
<th>Material properties</th>
<th>Grain</th>
<th>Short straw</th>
<th>Plate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg m(^{-3}))</td>
<td>1350</td>
<td>160</td>
<td>7850</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.25</td>
<td>0.45</td>
<td>0.29</td>
</tr>
<tr>
<td>Shear modulus (Pa)</td>
<td>(2.0 \times 10^8)</td>
<td>(4.4 \times 10^6)</td>
<td>(8.0 \times 10^{10})</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Collision properties</th>
<th>Grain–grain</th>
<th>Grain-plate</th>
<th>Short-straw-plate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficient of restitution</td>
<td>0.43</td>
<td>0.5</td>
<td>0.26</td>
</tr>
<tr>
<td>Coefficient of static friction</td>
<td>0.75</td>
<td>0.56</td>
<td>0.8</td>
</tr>
<tr>
<td>Coefficient of rolling friction</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
</tbody>
</table>

where \(\theta_i = 0\) or \(90^\circ\) was an orthogonal collision, in which the tangential overlaps \(\delta t\) and the tangential velocity \(v_t\) were zero. The tangential collision force \(F_{t1}\) was also zero and the direction of normal collision force \(F_{n1}\) was towards the grain centre, thus the grain was shown to rebound vertically after the collision. When \(0 < \theta_i < 90^\circ\), there was an oblique collision and a moment was generated by \(F_{n1}\), thus the particle rotated after the collision. Due to the occurrence of grain rotation, the normal collision force \(F_{n1\text{ max}}\) and contact time \(t_{1}\) both decreased. The initial parameters for the collision process were; angle of impact \(\theta_i = 30^\circ\), aspect ratio \(\gamma = 2\), \(v_{n1} = 2.5\) m s\(^{-1}\).

From Fig. 7 it can be seen that impact angle \(\theta_i\) has a significant influence on collision process. Deformation at the point of contact in the tangential direction, due to the effect of tangential velocity \(v_t\), also affects the collision process. Substituting Eq. (1) into Eq. (8), it can be seen that increasing \(R^*\), decreased of \(F_{n\text{ max}}\) and \(t_{1}\). When \(0 < \theta_i < 90^\circ\), the normal velocity and overlaps decreased because of the rotation of the grain, which led to \(F_{n1\text{ max}}\) decreasing. Along with the increases in \(\theta_i\), \(F_{n1\text{ max}}\) decreased, while \(F_{t1\text{ max}}\) increased. The contact time \(t_{1}\) also decreased. When \(\theta_i = 0\) or \(90^\circ\), the tangential contact force \(F_{t1}\) was zero. Due to a larger \(R^*\), \(t_{1}\) was relatively small.

Grain radius ratio \(\gamma\) was a significant factor influencing collision behaviour. To establish the effect of grain shape and collision angle on maximum collision force \(F_{n\text{ max}}\) during collision process, a defined peak force ratio \(\eta_i\) was defined as:

\[
\eta_i(\theta_i, \gamma) = \frac{\max(F_{n1}(\theta_i, \gamma))}{\max(F_{n1}(0, \gamma))} \times 100\% \quad (21)
\]

The larger \(\eta_i\), the more stable the values of \(F_{n1\text{ max}}\); the smaller \(\eta_i\), the greater differences in \(F_{n1\text{ max}}\). Substituting DEM simulation data, carried out at the conditions \(v_{n1} = 2.5\) m s\(^{-1}\),

### 4.2. Simulations of grains colliding with the sensitive plate

It was assumed that the angle between long axis of the grain and the collision plane was the impact angle, marked as \(\theta_i\).
\[ q = 1 - 4, \theta_1 = 0 - 90^\circ \] into (Eq. (21)), obtained the variations of \( \eta_1 \) shown in Fig. 9.

From Fig. 9 it can be see that \( \eta_1 \) monotonically decreased with increasing \( g \), which indicated that the differences in \( F_{n1} \) were more significant. At the collision point, the minimum \( \eta_1 (\eta_1 < 40\%) \) appeared when \( \theta_1 = 20^\circ - 40^\circ \) and \( \gamma = 3 \). Figure 10 shows variations of \( t_{r1} \) with increasing \( \theta_1 \). Overall, \( t_{r1} \) was distributed within 15–34 \( \mu s \); the minimum \( t_{r1} \) appeared in the range of \( \theta_1 = 20^\circ - 40^\circ \). Simulation results indicated that \( F_{n1} \) was distributed in the range 1.4 N–8.5 N.

### 4.3. Simulation of short straw collision with the sensitive plate

Short straws significantly influence the monitoring accuracy of the sensor. It was assumed that the angle between length direction of the straw and the collision plane was the impact angle, marked as \( \theta_2 \). Variations of \( F_{n2} \) and \( t_{r2} \) for short straw collisions with the sensitive plate at conditions of \( v_{n2} = 2.5 \) m s\(^{-1} \), straw length \( l = 10 - 90 \) mm, \( \theta_2 = 0 - 90^\circ \) are shown in Fig. 11. From Fig. 11(a) it can be seen that rise-time \( t_{r2} \) was relatively low when the impact angle \( \theta_2 = 0 \) or \( 90^\circ \), and force rise time \( t_{r2} \) increased with the increasing of straw length \( l \) when \( \theta_2 \) was fixed. It was also found that force rise time \( t_{r2} \) increased rapidly in the range of \( 0 < \theta_2 < 45^\circ \). It reached a relatively high value when \( \theta_2 = 45^\circ \), and then decreased with increasing \( \theta_2 \). From Fig. 11(b) it can be seen that along with the increasing of \( \theta_2 \), \( F_{n2} \) increased accordingly. At a certain collision angle, \( F_{n2} \) decreased rapidly as straw length \( l \) increased from 0 to 75 mm, and \( F_{n2} \) increased dramatically as straw length increased from 75 to 90 mm. Generally speaking, \( t_{r2} \) was distributed in the range 63–182 \( \mu s \) and \( F_{n2} \) was distributed in the range 0.1–1.2 N.

Similarly, to demonstrate the influence of straw length \( l \) and collision angle \( \theta_2 \) on peak contact force \( F_{n2} \) during collision process, a peak force ratio \( \eta_2 \) was defined as:

\[
\eta_2(\theta_2, l) = \frac{\max(F_{n2}(\theta_2, l))}{\max(F_{n2}(0, l))} \times 100\% \tag{22}
\]

From Fig. 12 it can be seen that along with the increasing of \( l \), \( \eta_2 \) decreased rapidly to about 30%. Because of the opposite directions of two moment generated by \( F_{t2} \) and \( F_{n2} \) when \( 0 < \theta_2 < 90^\circ \), the peak force ratio \( \eta_2 \) reached its minimum value in the range of \( 60^\circ < \theta_2 < 75^\circ \).

### 4.4. Free-fall experiments

To verify the DEM simulation results, collision experiments were carried out in laboratory. Material was allowed to fall from a height of 250 mm onto the sensitive plate. The output voltage signal was recorded by a storage digital oscilloscope (DS01022A, Agilent, Santa Clara, CA, USA) with a bandwidth 500 kHz. Due to high internal resistance of the piezoelectric ceramics and the weak collision signal, the collision signal should be converted into a low impedance signal and enlarged, otherwise the collision signal may be submerged by
other interference signals. A voltage amplifier was selected as preamplifier, simplified voltage amplifier circuit shown in Fig. 13.

In the above, the equivalent resistance of the piezoelectric ceramics \( R = \frac{R_a}{R_i} \), where \( R_a \) is the leakage resistance, \( R_i \) is the input resistance and the equivalent capacitance \( C = C_i + C_a + C_c \), where \( C_a \) is the capacitance of the piezoelectric ceramics, \( C_i \) is the input capacitance and \( C_c \) is cable capacitance.

Assuming that grain collision force \( F_n = F_{n_{max}} \sin \theta \) acts on a piezoelectric ceramic, then the generated charge and voltage on the piezoelectric ceramic surface is varied according to sinusoidal law, that is:

\[
q = d_{33}F \sin \theta
\]

Since \( i = dq/dt \), the voltage amplitude \( U_{max} \) is obtained as;

\[
U_{max} = \frac{d_{33}F_{n_{max}}R}{\sqrt{1 + (\omega RC)^2}}
\]

where \( \omega \) is the angular frequency of the signal vibration.

When \( R \to \infty \), the input voltage of operational amplifier \( A_1 \) can be expressed as:

\[
U_{max} = \frac{d_{33}F_{n_{max}}}{C}
\]

From Eq. (25) it can be seen that the output voltage is proportional to the maximum normal collision force \( F_{n_{max}} \).

The operational amplifier AD620an (Analog Devices, Inc., Norwood, MA, USA) is a low cost, high accuracy instrumentation amplifier that requires only one external resistor to set gains of 1–10,000. Furthermore, the packaging of AD620an is smaller than discrete designs and offers lower power (only 1.3 mA max supply current), making it a good choice for battery-powered, portable (or remote) applications.

The parameters of rice grains and short straws are shown in Table 2 and typical experimental results are shown in Fig. 14. It can be seen that the highest value of \( V_{out1} \) was 4.0 V with a \( t_{r1} \) of 14 ms, and the lowest value of \( V_{out1} \) was about 2.5 V with \( t_{r1} \) of 30 ms when a single collision occurred (grain 1 and grain 2 in Fig. 14, with semi-axes dimension of 3.75 × 1.6 × 1.1 mm, mass 29 × 10^{-3} g). Some experiments were carried out by using another rice grain (grain 3) with semi-axes 2.95 × 1.8 × 1.4 mm and mass 27.5 × 10^{-3} g. The typical variations of collision force were also found with this grain. Because of the smaller dimensions, the ranges of \( V_{out1} \) and \( t_{r1} \) were reduced to 1.8–3.5 V and 15–25 μs, respectively.

Typical experimental results for short straws with different lengths showed that the highest value of \( V_{out2} \) was below 1.5 V with \( t_{r2} \) of 130 ms, and the lowest value of \( V_{out2} \) was about 1.0 V with \( t_{r2} \) of 80 ms. Compared with simulation results in which \( t_{r1} \) was in the range 15–34 μs and \( t_{r2} \) in the range 63–182 μs, the...
experimenatl results were shown to be basically consistent with the DEM simulation results.

4.5. Design of a signal processing circuit

4.5.1. Filter circuit
From simulation results it can be seen that the rise time $t_{r1}$ of the grain collision signals was in the range 15–34 $\mu$s making the signal frequency of grain collisions in the range 7–16 kHz and the, signal rise time $t_{r2}$ within the range 63–182 $\mu$s. The straw collision signal frequency was in the range 1–4 kHz. Considering simulation errors, a fourth-order band-pass filter circuit with a corner frequency of 5–20 kHz was designed to discriminate out the grains. The filter circuit was designed using a reference handbook for filter design (Carter & Mancini, 2010) shown in Fig. 15.

4.5.2. Absolute value amplifier circuit
Peak voltage is another crucial index for characterising grain impact signals. Due to the stochastic nature of grain collisions and initial velocity, the generated signal peak voltages may be positive or negative. In order to accurately acquire the peak voltage, an absolute value amplifier consisting of a precision detector and an adder was developed, the circuit shown in Fig. 16. The principle of the absolute value amplifier circuit was as follows:

$$v_3 = \frac{R_5}{R_3} v_2 \quad (v_2 < 0) \quad (26)$$

$$v_3 = \left( \frac{R_1}{R_2} \frac{R_5}{R_4} \right) \cdot v_2 \quad (v_2 > 0) \quad (27)$$

4.5.3. Signal pulse shaping and square wave generator circuit
To avoid influence of impact resonance, an envelope detector was added to extract the signal envelope curve to reduce the counting error. The enveloped signal was then carried into a voltage comparator circuit to obtain a standard square wave signal. Standard square voltage pulse signals were sent to a microcontroller unit (MCU), based on AT89C52 (Atmel Co., San Jose, CA, USA) single chip microcomputer to count the number of grains, and the result was shown by using an instrument display. The sensitivity of the sensor could be adjusted by changing the threshold value of the comparator circuit, and local interference could be inhibited. The signal pulse shaping and square wave generating circuit is shown in Fig. 17. A diagram of the signal processing circuit is shown in Fig. 18.

4.6. Performance calibration experiments
To check performance of the signal processing circuit, experiments were carried out on a calibration bench. The
developed calibration test-bench mainly consisted of a conveyor with a velocity could be adjusted in the range 0–0.5 m s\(^{-1}\) and grain fall height adjusted in the range 150–350 mm. Seven groups of different materials were used as calibration material to test the ability of the sensor to discriminate full grains from complex mixtures of materials. The calibration test-bench is shown in Fig. 19.

In the calibration experiments, material was dropped from a height of 250 mm for less than 10 s and the sensor mounting angle was 45\(^\circ\). Each calibration test was repeated three times and average values obtained. Measurement errors in different materials were shown in Table 3. The calibration material was composed of 500 full grains with semi-axes dimensions of 2.95 \(\times\) 1.8 \(\times\) 1.4 mm and mass 27.5 \(\times\) \(10^{-3}\) g; 500 full grains with semi-axes dimension of 3.75 \(\times\) 1.6 \(\times\) 1.1 mm, mass 29 \(\times\) \(10^{-3}\) g and short straws with different lengths in the range 30–90 mm.

From Table 3 it can be seen that the blighted grains, short straws and long straws had no effect on the accuracy of full grain detection, the signals generated by those collisions can be filtered; for materials 4,5,6,7, the full grains that may not fall onto the sensor surface and resulting in a leakage, while

<table>
<thead>
<tr>
<th>Material</th>
<th>Sample amount</th>
<th>Detected amount within 10 s</th>
<th>Relative error for detecting rice grains (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Blighted grains</td>
<td>1000 grains</td>
<td>0</td>
<td>/</td>
</tr>
<tr>
<td>2. Short straws</td>
<td>10 g</td>
<td>2 g</td>
<td>/</td>
</tr>
<tr>
<td>3. Long straws</td>
<td>10 g</td>
<td>1 g</td>
<td>/</td>
</tr>
<tr>
<td>4. Full grains + blighted grains</td>
<td>1000 grains + 1000 grains</td>
<td>975 grains</td>
<td>2.5</td>
</tr>
<tr>
<td>5. Full grains + short straws</td>
<td>1000 grains + 10 g</td>
<td>971 grains</td>
<td>2.9</td>
</tr>
<tr>
<td>6. Full grains + long straws</td>
<td>1000 grains + 10 g</td>
<td>984 grains</td>
<td>1.6</td>
</tr>
<tr>
<td>7. Full grains + blighted grains + short straws + long straws</td>
<td>1000 grains + 1000 grains + 10g + 10g</td>
<td>967 grains</td>
<td>3.3</td>
</tr>
</tbody>
</table>
some grains falling with a relative high velocity may collide with the sensor be ejected and then, collide with the sensitive plate again because of interactions among grains and MOG. However, the collision velocity was relatively small because of interactions, the voltage amplitude of the secondary collision generated signal was generally less than the threshold voltage of the voltage comparator circuit. Therefore, some grains would not cause an effective collision, and leading to measurement errors. Overall, the sensor has a good ability in discriminating full grains from complex mixtures of materials.

5. Development of monitoring mathematical model

5.1. Test-bench experiments

Understanding the relationship between counted grain numbers and the total grain sieve loss is essential for monitoring the grain losses in real-time. To apply a grain sieve loss monitoring mathematical model, laboratory experiments were carried out on a longitudinal-axial threshing–separating-cleaning test-bench with a tangential feed. The test-bench was made up of conveyor, a feeding stir rope, a conveying channel, a tangential rotor, a cleaning system, boxes to acquire cleaning outputs, and a load test system to measure the power consumption of each rotor. The diameter of the tangential rotor was 544 mm, and its length was 960 mm, the concave arc corner of the gravure screen grid was 800. The diameter of the axial rotor was 626 mm, and its length was 1790 mm; the concave arc corner of the gravure screen grid was 2000. The threshing component had trapezoidal teeth. The threshing gap of the tangential rotor could be set to 15, 21 and 27 mm and the threshing gap of axial rotor could be set to 8, 14, and 20 mm. The speeds of revolution of the tangential and axial rotors had 3 combinations which could be adjusted to 893/849 rpm, 808/768 rpm and 723/687 rpm, respectively. The schematic diagram of test-bench was shown in Fig. 20.

Analysis was performed to study influence of threshing gap of tangential rotor, revolution speed of tangential rotor and axial rotor, and threshing gap of axial rotor on power consumption and separation loss. Experimental results showed that the rotational speed of the rotors was the main factor influencing power consumption and separation loss. The combine had an optimal threshing and separation performance when the rotational speed of the tangential rotor was 893 rpm, the threshing gap of tangential rotor was 21 mm, threshing gap of the longitudinal rotor was 20 mm, and rotational speed of the longitudinal rotor was 849 rpm. Properties of experimental rice used are shown in Table 4.

Previous researches has shown that fan speed has a paramount influence on grain sieve losses. Thus, due to experimental limitations, the influence of fan speed on sieve losses was mainly considered. In experiments, rice collected from the same field as above was used. The properties of rice are shown in Table 3. Fresh material was uniformly spread over a conveyor surface (10 m long and 1.2 m wide) with a feeding quantity of 7 kg s$^{-1}$. It was fed into the threshing unit using an intake chain conveyor with a constant velocity 1 m s$^{-1}$, the tangential rotational speed was 893 rpm, the tangential threshing gap was 21 mm, the longitudinal threshing gap was 20 mm, and the longitudinal rotational speed was 849 rpm. Fan speeds of 1200 rpm, 1300 rpm and 1400 rpm were used by changing driving wheels with different diameters. In the experiment, a canvas was used to separate outputs from the cleaning shoe and the separation shoe and 84 boxes (in a 12 x 7 matrix) were added to collect the output from the cleaning shoes. The grains were removed from each box used re-cleaner (Agriculex ASC-3 Seed Cleaner, Guelph, Ontario, Canada). Each experiment was repeated 3 times and the averaged values from each box obtained. Cleaned grains from each box were placed on a tablecloth in accordance with the original order as shown in Fig. 21(a). The distribution of grain losses with a fan speed of 1200 rpm is shown in Fig. 21(b).

![Fig. 20 – Overall design of tangential-longitudinal axial test-bench and location of the material receiving boxes, 1. reel, 2. header, 3. operating system, 4. header auger, 5. motor, 6. tangential separating threshing unit, 7. chassis, 8. cleaning fan, 9. vibrating sieve, 10. grain auger, 11. axial separating threshing unit, 12. tailings auger, 13. material receiving boxes.](image)

<table>
<thead>
<tr>
<th>Table 4 – Properties of experimental rice.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rice variety</td>
</tr>
<tr>
<td>Grain moisture content (%)</td>
</tr>
<tr>
<td>MOG moisture content (%)</td>
</tr>
<tr>
<td>Average length of the stems (mm)</td>
</tr>
<tr>
<td>MOG/grain mass ratio</td>
</tr>
<tr>
<td>Thousand seed mass (g)</td>
</tr>
<tr>
<td>Grain yield (kg ha$^{-1}$)</td>
</tr>
</tbody>
</table>

![Table 4 – Properties of experimental rice.](image)
5.2. Installed position of the sensor in X direction

The grain loss monitoring sensor was placed on the rear rack of cleaning shoe, under the sieve. The sensor was fixed and did not moving with the sieve. Since detecting speed of the sensor was constant, proper grain flow in the sensor mounted position was critical for monitoring whole grain sieve loss. Using experimental data obtained from experiments with fan speed of 1200, 1300, 1400 rpm, obtained grain loss distributions varying along the X axis direction shown in Fig. 22.

From Fig. 22 can be seen that in the leading segment ($x < 0.26$ m), grain loss increased more rapidly and the variation of cumulative distribution was larger and it was more difficult to detect the grains precisely. In the trailing segment ($x > 0.52$ m), the amount of grain loss was reduced, but MOG was high, also the difficulty for a sensor to detect grains from the massive amounts of MOG increased. In the middle segment ($0.26 < x < 0.52$ m), grain flux was more modest and stable. To monitor current grain loss accurately, the sensor should be fixed in the middle segment with $0.26 < x < 0.52$ m.

5.3. Probability distribution of the grains along the X-axis

The grain mass ratio in boxes of each column along the Y-axis direction accumulated together got the grain mass ratio distribution along the X-axis direction. Calculated results showed that fan speed had a slight influence on the distribution of grain loss along X-axis, which means that the grain mass ratio was nearly the same along X axis for the different fan speeds. The probability distribution model for the grain loss mass ratio under different fan speeds along the X-axis can be expressed by:

$$s_f(x) = A(1 - e^{-k(x-x_c)})$$  \hspace{1cm} (28)

In Eq. (28), $A$, $x_c$, $k$ are constants, nonlinear fitting carried out using Origin 8.0 software (OriginLab Corporation, Northampton, MA, USA) and got $A = 0.99411$, $x_c = 0.06365$, $k = 4.92728$, $R^2 = 0.99971$, nonlinear fitting result shown in Fig. 23.

5.4. Probability distribution of grains along the Y-axis

When $0.26$ m < $x$ < $0.52$ m, the accumulated grain mass ratio in the boxes from each column were obtained along the X-axis direction and the grain mass ratio distribution obtained along the Y-axis for fan speeds of 1200, 1300 and 1400 rpm. The probability distribution model for grain loss mass ratio under different fan speeds along the Y-axis can be expressed by:

$$s_r(y) = Be^{-y/t_1} + y_0$$  \hspace{1cm} (29)

where $B$, $y_0$, $t_1$ are constants, and come from experimental data using nonlinear fitting carried out using Origin 8.0 software. The values obtained from the tests were $y_0 = -7.95427$. 
B = 8.06237, t₁ = −8.8689 with R² = 0.99299. The nonlinear fitting result is shown in Fig. 24.

5.5. Monitoring the grain cleaning loss

Associated Eqs. (28) and (29), loss grains ratio in the monitoring area can be expressed as:

\[ r = s_y(x) \left( \frac{x_0 + a/2}{x_0 - a/2} \times s_r(y) \right)^b \mid_{0.26 < x_0 < 0.52} \]

(30)

where, \( x_0 \) was the central position of monitoring area; \( a, b \) were the length and width of the sensor. As long as \( x_0, a \) and \( b \) are known, the ratio between grain loss in the monitoring area and total grain loss can be calculated according to Eq. (30), then converted into the total cleaning grain loss in real-time. A schematic diagram of the monitoring method is shown in Fig. 25.

5.6. Field experiments

To benchmark the monitoring accuracy of the developed sensor, experimental results were obtained comparing absolute sieve loss values obtained by collecting all the discharged material and observed values measured by the developed sensor. The grain sieve loss monitoring sensor was mounted on a combine harvester (Model: 4LZ-3.5, Wuxi Combine Harvester Co., Ltd, Wuxi, China), as shown in Fig. 26. The machine had the same structural parameters as the test-bench mentioned above. The horizontal and vertical distances between sensor centres and sieve end were 250 mm in the installation, and the mounting angle was 45°. According to grain sieve loss monitoring model shown by Eq. (30), \( r = 0.121 \). The harvesting distance was 10 m with a constant fan speed of 1300 rpm.

Before field experiments, preparatory work was carried out. A canvas was used to separate outputs from separation and cleaning shoes, as shown in Fig. 21, and the average grain separation loss in 10 m was obtained following adjustment of some parameters to ensure an optimal combination according to test bench results and experience. The threshold voltage of signal processing circuit was adjusted until the value displayed on the display instrument was about 1–2 grains, which indicated that the system could overcome vibrational interference. In experiment, a piece of canvas was used to collect all the mixed materials at the outlets, then the full grains were filtered out from MOG using the stationary re-cleaner (Agriculture ASC-3 Seed Cleaner), weight and subtracted the separation losses. Finally, the current grain sieve losses were calculated. Based on the sensor counting grain numbers and the mathematical model, total sieve losses were displayed on the instrument’s display. Properties of experimental rice used were given in Table 5. Table 6 shows an error analysis of the

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</tr>
<tr>
<td>Thousand seed mass (g)</td>
</tr>
<tr>
<td>Grain yield (kg/hm²)</td>
</tr>
</tbody>
</table>

Fig. 24 – Cumulative of grain mass ratio in Y axis.

Fig. 25 – Schematic diagram of monitoring method. 1. sieve, 2. grain loss monitoring sensor.

Fig. 26 – Installation position of the sensor and image of the field tests.
averaged results acquired by the sensor and manually using the same operating parameters of replicated three times. Test 1 was carried out using “Nan Jing” rice and test 2 with “Long Jing” rice.

From Table 6 can be seen that measurement error increased with increasing combine forward speed, but the relative measurement error was <4.48%, which indicated that the developed rice grain monitoring system well worked. Due to the complexity of the cleaning process, the grain numbers counted by the sensor was not a constant value. This was because dropped grains may collide again with the sensitive plate due to interaction among grains and MOG. Also, because of the rugged ground, the combine harvester could produce severe movements in the sensor device during field operation, which could cause a failure of the isolation device, resulting in large measurement errors.

Zhao, Li, Liang, and Chen (2012) who developed a grain impact sensor utilising a polyvinylidene fluoride (PVDF) piezoelectric-film as sensing element to monitor grain sieve losses on a tangential-longitudinal axial combine harvester (Model: 4LQZ-6 Foton Lovol International Heavy Industry Co., Ltd, China) found a large area of moist powder accumulating on the PVDF film surface and a measurement error up to 10.6%. Li, Chen, Zhao, and Xu (2013) installed a grain sieve loss monitoring sensor at the end of the sieve on a tangential-longitudinal axial combine harvester (Model: 4L-3.5 (TH988) Wuxi Combine Harvester Co., Ltd, China) and found a relative measurement error up to 19.35%. Hence the values found here indicate that the developed rice grain sieve loss monitoring system appeared to function well.

Table 6 – Error analysis of sieve loss obtained by the sensor compared to manual measurement.

<table>
<thead>
<tr>
<th>Tests No.</th>
<th>Forward speed m s⁻¹</th>
<th>Sieve losses</th>
<th>Relative error/%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Sensor</td>
<td>Manual</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total amount</td>
<td>Total mass g</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ratio %</td>
<td>Ratio%</td>
</tr>
<tr>
<td>1#</td>
<td>0.60</td>
<td>611</td>
<td>1.0020</td>
</tr>
<tr>
<td></td>
<td>0.75</td>
<td>671</td>
<td>1.1008</td>
</tr>
<tr>
<td></td>
<td>1.00</td>
<td>778</td>
<td>1.2764</td>
</tr>
<tr>
<td>2#</td>
<td>0.60</td>
<td>320</td>
<td>0.4412</td>
</tr>
<tr>
<td></td>
<td>0.80</td>
<td>589</td>
<td>0.8121</td>
</tr>
<tr>
<td></td>
<td>1.00</td>
<td>658</td>
<td>0.9081</td>
</tr>
</tbody>
</table>

6. Conclusion

A grain sieve loss monitoring sensor based on YT-5L piezoelectric ceramics as the sensing element was designed. DEM simulation results indicated that the oblique collision process consists of four period basically: free falling, collision, rebound, and rotating; and there are distinct differences between rice grain particles and short straws in t₁ and Fₙmax; for rice grain, the Fₙ₁ max was in the range 1.4 N–8.5 N and t₁₁ in the range 15–34 μs; for short straw, the Fₙ₂ max was in the range 0.1 N–1.2 N, t₂₀ was in the range 63–182 μs. Using differences in normal collision force Fₙmax and force rise-time tₐ, a signal processing circuit which mainly consisted of a band-pass filter circuit with corner frequencies of 5–20 kHz and threshold value adjustable voltage comparator circuit designed to discriminate the full grain out was designed. The grain loss monitoring system was mounted on a combine harvester and utilising the mathematical model developed based on the laboratory test-bench experiments results, field tests carried out. The field test results indicated that the measurement errors were <4.48%.

Acknowledgements

This research was supported by the National Natural Science Foundation of China (51375214, 51475217), the Graduate Innovative Projects of Jiangsu Province 2014 (KYLX _1021), Fok Ying-Tong Education Foundation, China (Grant No. 141051) and A Project Funded by the Priority Academic Program Development of Jiangsu Higher Education Institutions (PADP). Thanks for all your support.

REFERENCES


