DESIGN AND EXPERIMENT OF CENTRIFUGAL COLLISION TEST DEVICE FOR MILLET AND SWEET BUCKWHEAT GRAIN
/
谷子、荞麦籽粒离心式碰撞试验装置设计及试验

Sun Jingxin [1], Yang Liqin [2], Xu Baohui [1], Guo Yuming *[3], Cui Qingliang [3], Zhang Yanqing [3] [1]
[1] Department of Mechanical and Electrical Engineering, Yuncheng University, Yuncheng 044000, China;
[2] Planning Finance Office, Yuncheng University, Yuncheng 044000, China;
[3] College of Agricultural Engineering, Shanxi Agriculture University, Taigu 030801, China;
Tel: +86-0354-6286869; E-mail: guoyuming99@sina.com
DOI: https://doi.org/10.35633/inmateh-65-20

Keywords: *millet grain, sweet buckwheat grain, collision, crushing rate, threshing*

ABSTRACT

This critical collision damage force of millet and sweet buckwheat grain and the shelling force of shelled granular materials are important basic data for research of threshing and shelling technology and equipment. In order to master the linear velocity and collision force of grain with different moisture content when collision damage occurs, a centrifugal collision test device is designed. Based on the dynamic and kinematic analysis of grain in the centrifugal rotary table, the collision force between grain and steel plate was measured by PVDF piezoelectric pressure sensor and data acquisition system. The results showed that: under the same moisture content, the higher the rotational speed, the higher the grain crushing rate; at the same rotational speed, with the increase of moisture content, the crushing rate first decreased and then increased. When the moisture content of Jingu-21 and Yuqiao-4 is 19.7% and 17.8%, respectively, the grain crushing rate was the lowest. In terms of the anti-collision ability of grain, the optimum moisture content of threshing is between 19.7% and 21% for millet. For sweet buckwheat, the optimum moisture content of threshing is 17.8% ~19%, while the optimum moisture content of shelling by centrifugal sheller is about 11%. The faster the rotational speed of centrifugal rotary table is, the greater the linear speed of grain is, and the greater the collision force is. When the linear velocity of grain was 8.32 m/s and 11.30 m/s respectively, the millet grain moisture content was 11.1% and 20.9% respectively, damage began to appear, and the corresponding collision force was about 5.51 N and 10.6 N, respectively. When the linear velocity of grain was 8.32 m/s and 11.30 m/s respectively, and the moisture content was 11.1% and 22.8% of the sweet buckwheat grain respectively, damage began to appear, the corresponding collision force was about 8.92 N and 12.79 N, respectively. When the rotating speed of rotary table was 910 r/min, the linear speed of grain was 27.05 m/s, the crushing rate of millet and sweet buckwheat grain in harvest period were 56.30% and 63.76%, respectively, and the crushing rate of millet and buckwheat grain with 11.1% moisture content were 86.27% and 89.4%, respectively. The research results can provide theoretical basis for design and optimization of millet and sweet buckwheat combine harvester, threshing device and shelling device.

摘要

谷子、荞麦籽粒的临界碰撞损伤力及带壳散体物料的破壳力是研究脱粒、脱壳技术及其装备的重要基础数据。为掌握不同含水率的籽粒出现碰撞损伤时的线速度、碰撞力等，该文设计了一种离心式碰撞试验装置，对籽粒在转盘内进行动力学及运动学分析的基础上，采用 PVDF 压电薄膜传感器及数据采集系统对籽粒与钢板的碰撞力进行了测定。结果表明：同一含水率下，转速越大，籽粒的破碎率越高；在同一转速下，随着含水率的增大，破碎率先减小后增大，晋谷 21 号、榆荞 4 号的含水率分别为 19.7%、17.8%时，籽粒的破碎率最小；从籽粒的抗碰撞能力来说，对于谷子，脱粒的最佳含水率在 19.7%～21%之间；对于甜荞麦，脱粒的最佳含水率在 17.8%～19%之间，而采用离心式脱壳机脱壳时的最佳含水率在 11%左右。离心式转盘的转速越快，籽粒的线速度越大，所受的碰撞力也越大；当籽粒的线速度分别是 8.32 m/s、11.30 m/s 时，含水率分别为 11.1%、20.9%的谷子籽粒开始出现损伤，对应的碰撞力分别是 5.51N、10.6 N 左右；当籽粒的线速度分别是 8.32

[1] *JingXin Sun, Lec. Ph.D. Eng.; Liqin Yang, Assis accoun. M.B.A.Eng.; BaoHui Xu, Prof. Ph.D. Eng.; YuMing Guo, Prof. Ph.D. Eng.; QingLiang Cui, YanQing Prof. Ph.D. Eng.; Zhang, Lec. Ph.D. Eng.*

m/s、11.30 m/s 时，含水率为 11.1%、22.8%的甜荞麦籽粒出现损伤，对应的碰撞力分别是 8.92N、12.79 N 左右；当转盘转速为 910 r/min 时，籽粒的线速度为 27.05m/s，收获期谷子、甜荞麦籽粒的破碎率分别为 56.30%、63.76%，含水率均为 11.1%的谷子、甜荞麦籽粒的破碎率分别为 86.27%、89.4%。研究结果可为谷子和荞麦的联合收获机、脱粒装置及脱壳装置的设计、优化提供基础依据。

INTRODUCTION

Millet and sweet buckwheat are special grain crops and important economic crops to increase farmers' income in some areas of China *(Ji et al., 2016; Domingos et al., 2021, Joshi et al., 2019; Rajasekaran et al., 2021)*. At present, the harvesting mechanization level of millet and sweet buckwheat is low *(Du et al., 2018; Lu et al., 2020)*, and the special combine harvesters are few *(Li et al., 2020)*. Most of them adopt the parameters and structure of improved grain and wheat combine harvester to harvest millet and sweet buckwheat *(Du et al., 2018; Huang et al., 2018; Hyeon et al., 2015).*

There are still some problems in mechanized harvest of millet and buckwheat, such as high loss of threshing and cleaning, high crushing rate of threshing and high impurity rate *(Liang et al., 2015; Zhang et al., 2019; Lu et al., 2017)*. Through the development and test of cleaning test device, the suspension speed range of millet and Buckwheat under different moisture content, the optimal speed of fan and the loss rate of grain were determined *(Hou et al., 2018; Li et al., 2018)*.

Grains are crushed and damaged by extrusion and impact of working parts during threshing of millet and buckwheat *(Fan et al., 2019; Sun et al., 2017; Sun et al., 2018; Xu et al., 2013)*. There are studies that show very clearly that the friction coefficient had little effect on the collision dynamics of single grain, the maximum collision force between grain and tooth in normal and tangential directions is not synchronized, the higher the roller speed is, the greater the normal impact force is *(Qian et al., 2017)*. The recovery coefficient of corn grain was determined by Wang based on high-speed camera system and the function derived from the velocity of corn grain in the direction of grain-grain collision contact force *(Wang et al., 2018)*. The maximum impact forces of corn grain were reduced with the increase of the moisture content. Different internal structure and shape of corn seed lead to different ability of resisting impact rupture of different varieties *(Li et al., 2009)*. The velocity of corn grain before and after collision was obtained through studying the motion state of corn grain after collision with threshing element and stalk in roller using high speed camera technique *(Jiang et al., 2011)*. Lizhang Xu used HyperMesh pre-processing software and LS-DYNA dynamic analysis program to simulate and analyse the rice grain, and established the compression displacement and maximum stress distribution when rice grain collided with tooth *(Xu et al., 2013)*. The critical velocity formula of impact damage between rice grain and threshing components can be deduced by *Contact Theory*, and the bench test of different varieties of rice grain is carried out. The test results are basically consistent with the calculation results *(Xu et al., 2009)*. The varieties and moisture content of sunflower have significant effects on rupture *(Li et al., 2018)*. Tao used the self-made centrifugal device to study the shelling of peony seeds, and obtained the optimal combination of motion parameters when the shelling rate was the highest and the kernel breaking rate was the lowest *(Tao et al., 2018)*.

However, there are few reports about the determination of grain impact force of millet and buckwheat. Therefore, millet and buckwheat grains were tested on the self-made centrifugal collision test bench. By using PVDF piezoelectric pressure sensor to measure accurately the collision force between grain and steel plate, and taking grain crushing rate as index, rotating speed and moisture content as independent variables, the moisture content and rotating speed of grain crushing rate were obtained with the minimum grain crushing rate. These results can provide a basic basis for the development and improvement of threshing shelling techniques and equipment of millet and buckwheat.

MATERIALS AND METHODS

Test materials and equipment

The test samples are harvested from the test field during the suitable harvest period. In order to prevent mechanical damage, after the samples are manually rubbed and threshed, the intact and full seeds without insect damage are selected, sealed with double sealing bags and placed in low temperature (1ºC±0.5ºC) environment. The variety of millet used in the test is Jingu-21, with moisture content of 11.1%, 15.2%, 17.5% and 20.9%. The variety of buckwheat used in the test is Yuqiao-4, with moisture content of 11.1%, 15.6%, 19.4% and 22.8%. The test equipment includes self-made centrifugal collision device and data acquisition system.

Overall structure and working principle

The centrifugal collision device is mainly composed of guide cone, centrifugal rotary table, centrifugal blade, collision baffle, retaining ring, adjustable speed motor, governor and frame. The power provided by the adjustable speed motor drives the spindle to rotate, and the spindle drives the centrifugal turntable to rotate. The speed of the centrifugal turntable is adjusted by the governor.

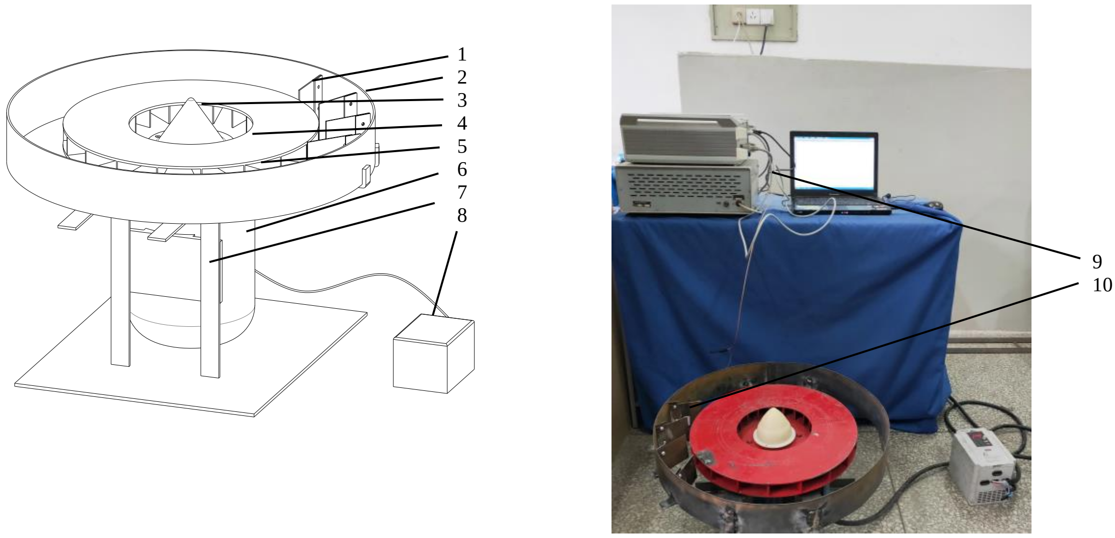


Fig. 1 - Structure diagram of centrifugal collision device

1 – Collision baffle; 2 – Retaining ring; 3 – Guide cone; 4 – Centrifugal rotary table; 5 – Centrifugal blade; 6 – Adjustable speed motor; 7 – Frame; 8 – Governor; 9 – Data acquisition system; 10 –. PVDF piezoelectric pressure sensor

During measurement, turn on all power supply, adjust the rotary table speed to the designed speed of test by governor. After the rotating speed of the turntable is uniform, release the grain at 1cm above the guide cone at a still position, and place the receiving box under the impact plate, observe and record the voltage value in the data acquisition software.

Key component design

The adjustable structural parameters of centrifugal turntable mainly include the diameter of rotary table, the tilt angle of blades, the number of blades and the height of blades. According to the triaxial size and 1000 grain weight of buckwheat and millet *(Sun et al., 2017; Sun et al., 2018)*, the parameters of centrifugal turntable were determined as follows: the outer diameter of centrifugal turntable is 400 mm, the inner diameter is 200 mm, the blade is installed in front 10°, the number of blades is 18, the blade height is 18 mm, the blade thickness is 2 mm, the structure diagram of centrifugal turntable is shown in figure 2.

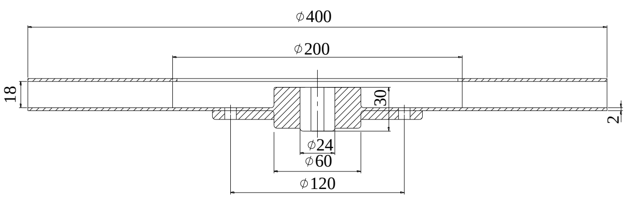


Fig. 2 - Structure diagram of centrifugal rotary table

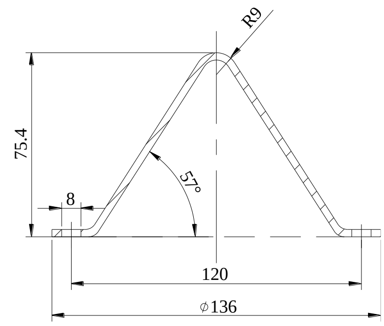


Fig. 3 - Structure diagram of guide cone

The guide cone mainly acts as buffer and shunt. When the grain falls along the surface of the guide cone, the grain enters the centrifugal turntable at a horizontal speed, which can effectively avoid the direct collision between the grain and the upper surface of the centrifugal turntable. The outer diameter of the guide cone is 136 mm, the height is 75.4 mm, and the sliding friction angle and rest angle between millet, buckwheat and Q235 steel plate are less than 40° according to the structure and size of the rotary table. For the grain to slide more easily, the angle between the guide plate and the horizontal plane is 57°, as shown in Figure 3.

Assume that the number of grains flying out of each pore is the same. There are four adjustable baffles installed on the outside of the rotary table. According to the calculated angle between the absolute velocity of grain leaving the rotary table and the circumference velocity φ_2, the angle adjustment range is 40°~50°. A PVDF piezoelectric pressure sensor installed on one of the baffles to measure the load of grain colliding with steel plate. The collision baffle is shown in figure 4.

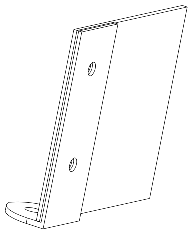


Fig. 4 - Structure diagram of collision baffle

Grain dynamics and kinematics analysis

After entering the centrifugal rotary table through the guide cone, the grain not only rotates around the axis at a constant speed with the rotary table, but also does linear motion along the blade away from the circle centre. Therefore, the grain of millet has a complex motion in the hole of the rotary table, and its motion trajectory is a complex curve. Force analysis of grain in the rotary table is shown in figure 5.

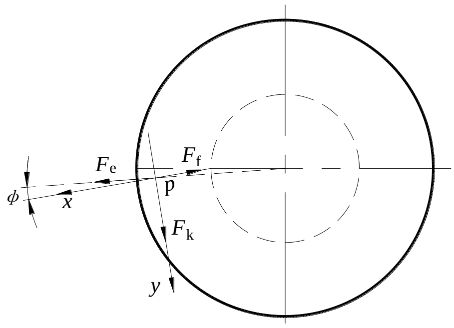


Fig. 5 - Force analysis diagram of grain in the rotary table

In order to analyse the force of the grain in the rotary table, the Cartesian coordinates xoy is established. The position of the grain in the rotary table is *p*, passing point *p* is X-axis along the blade direction and y-axis perpendicular to the blade direction. It can be obtained from Fig. 5.

$$\boldsymbol{F}_k + \boldsymbol{F}_e + \boldsymbol{F}_f = m\boldsymbol{a}_c \text{ [N]} \tag{1}$$

$$\boldsymbol{F}_k = m\boldsymbol{a}_k = 2m\omega\boldsymbol{v}_c = 2m\omega\frac{dr}{dt} \text{ [N]} \tag{2}$$

$$\boldsymbol{F}_e = m\boldsymbol{a}_e = m\omega^2 r \text{ [N]} \tag{3}$$

$$\boldsymbol{F}_f = \boldsymbol{F}_1 + \boldsymbol{F}_2 \text{ [N]} \tag{4}$$

$$\boldsymbol{F}_1 = \mu mg, \quad \boldsymbol{F}_2 = \mu\left(\boldsymbol{F}_k - \boldsymbol{F}_e \sin\phi\right) \text{ [N]} \tag{5}$$

where: $\boldsymbol{F}_k$ is Coriolis force on grain movement, [N];

$\boldsymbol{F}_e$ is centrifugal force on grain movement, [N];

$\boldsymbol{F}_f$ is friction on grain movement, [N];

$\boldsymbol{F}_1$ is friction caused by grain gravity, [N];

$\boldsymbol{F}_2$ is friction caused by Coriolis force and centrifugal force, [N];

m is quality of a grain, [kg];

$\boldsymbol{a}_c$ is relative acceleration of grain in the rotary table, [m/s²];
$\boldsymbol{a}_k$ is Coriolis acceleration, [m/s²];
$\boldsymbol{a}_e$ is centrifugal acceleration, [m/s²];
$\boldsymbol{v}_c$ is radial velocity vector of grain centre of gravity relative to the rotary table, [m/s];
ω is angular velocity vector of the rotary table, [rad/s];
r is the distance between grain centre of gravity and circle centre of the rotary table, [m];
μ is friction coefficient between grain and rotary table blade;
φ is the angle between centrifugal force and rotary table blade, [°].

The formula (1) is decomposed along the x-axis:

$$\boldsymbol{F}_k \cos\phi - \boldsymbol{F}_f = m\boldsymbol{a}_c \tag{6}$$

Substitute (2), (3), (4), (5) into (6) to:

$$m\omega^2 r\cos\phi - \mu mg - 2\mu m\omega\frac{dr}{dt} + \mu m\omega^2 r\sin\phi = m\frac{d^2r}{dt^2} \tag{7}$$

Simplified:

$$\omega^2 r\cos\phi - \mu g - 2\mu\omega\frac{dr}{dt} + \mu\omega^2 r\sin\phi = \frac{d^2r}{dt^2} \tag{8}$$

According to the triangle cosine theorem, the absolute velocity of grain is:

$$v_0 = \sqrt{v_c^2 + v_e^2 - 2v_c v_e\cos\phi_1} \quad \text{[m/s]} \tag{9}$$

where: $\boldsymbol{v}_0$ is the absolute speed of grain leaving the rotary table (p point), [m/s];
$\boldsymbol{v}_e$ is circumferential velocity of grain at p point, [m/s];
φ_1 is complementary angle at angles v_c and v_e, [°]
When the grain moves to the edge of the turntable, the speed diagram is shown in Fig. 6

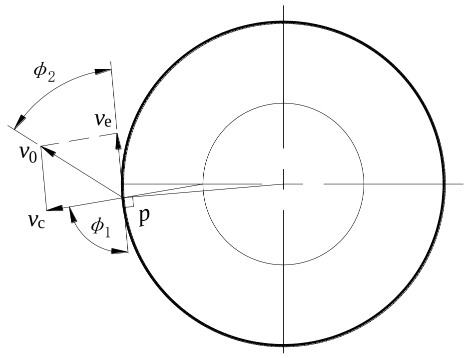


Fig. 6 - Speed diagram of grain at the edge of the rotary table

The φ_2 is the angle between v_0 and v_e, and its calculation formula is:

$$\phi_2 = \arctan\frac{v_c\sin\phi_1}{v_e - v_c\cos\phi_1} \tag{10}$$

The circumference velocity v_e of grain at p point as follows:

$$v_e = 2\pi Rn/60 \tag{11}$$

where: R is the calculated radius of the rotary table, [m]; n is rotating speed, [r/min];

According to the empirical formula of centrifugal sheller, the absolute velocity of grain is as follows:

$$v_0 = \pi Dn(1+\delta)/60 \tag{12}$$

where: D is the calculated diameter of the rotary table, [m];
δ is the composite factor, 0.42;

When the grain leaves the turntable, the angle φ_2 between absolute velocity v_0 and the circumference velocity v_e is as follows:

$$\phi_2 = \arccos\frac{v_e}{v_0} = \arccos\frac{1}{1+\delta} = 45.23° \tag{13}$$

Method and Principle of Centrifugal Collision Test

The data acquisition system is composed of HT-1712H DC power supply (DC 12 V), TST high speed data collector and “DPA5.11” data acquisition software. The principle is to connect the amplifier signal to the data collector, and the collector uploads the signal to the computer through the TCP/IP protocol by Ethernet interface. The sampling frequency is 1 kHz. The advantages and disadvantages of piezoelectric ceramic sensor *(Liang et al., 2016)* and PVDF piezoelectric pressure sensor *(Cao et al., 2019)* are compared. Finally, it is determined that the force measuring device is composed of PVDF piezoelectric pressure sensor and VK101H charge amplifier (Output voltage ±5 V, sensitivity 10 pC/100mV,1,2,4,8,11 times amplified by adjusting dial switch). The amount of charge can be calculated by the following formula:

$$C_{in} = \frac{V_{out} \cdot A_c}{G_{ain}} \tag{14}$$

where: C_{in} is the amount of charge that grain collide with the sensor, [pC] ($1C=1\times10^{12}$ pC);
V_{out} is the voltage that grain collide with the sensor, [V];
A_c is amplifier Sensitivity, [10 pC /100mV];
G_{ain} is magnification of the amplifier setting

The collision force can be calculated by formula (15) to obtain:

$$F_p = C_{in}/20 \tag{15}$$

where: $\boldsymbol{F}_p$ is collision force, [N];

RESULTS

Test results and analysis

The receiving box is installed under the collision plate, mainly to collect the grains that collide on the collision plate after being thrown out by the rotary table. After the experiment was completed, the crushing degree of grain was observed under stereomicroscope. Finally, according to the formula (21), the crushing rate of different moisture content under different speeds was calculated.

$$p = \left[m_1/\left(m_1 + m_2\right)\right] \times 100\% \tag{16}$$

where: p is crushing rate, [%];
m_1 is total quality of broken grains, [kg];
m_2 is total quality of unbroken grains, [kg];

The voltage signal and time curve of single grain impact collected by data acquisition system is shown in figure 7.

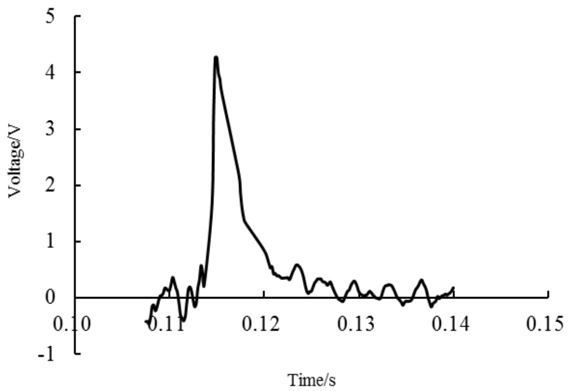


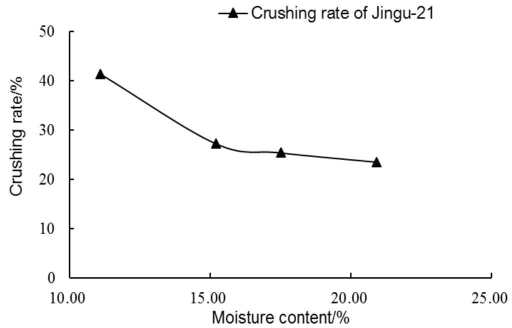
Fig. 7 - Curve of voltage value produced by single grain impact and time

Table 1

Experimental results of millet and buckwheat grains crushing rate under different speed

Variety	Moisture content/%	Speed [r/min]						
		120	280	380	580	660	780	910
Crushing rate of Jingu-21	11.1%	0.0%	0.11%	5.77%	15.38%	41.03%	56.82%	86.27%
	20.9%	0.0%	0.0%	1.69%	12.21%	23.53%	29.46%	56.30%
Crushing rate of Yuqiao-4	11.1%	0.0%	2.58%	20.90%	29.29%	48.20%	68.08%	89.4%
	22.8%	0.0%	0.0 %	3.81%	16.14%	30.70%	39.02%	63.76%

It can be seen from Table 1 that under the same moisture content, the higher the rotational speed, the higher the grain crushing rate of millet and buckwheat grain, which is consistent with the results of Chen *(Chen, 2019)* and Guo *(Guo et al., 2005)*. At the same rotational speed, the crushing rate of grain with high moisture content is smaller than that of low moisture content. This is due to the high hardness and low toughness of the grain when the moisture content is low, the elastic deformation is mainly occurred in the collision, and the deformation is small. When the moisture content is high, the grain hardness is small, the toughness is high, the plastic deformation occurs mainly during the collision, and the deformation is large. For the purpose of studying the variation of crushing rate with moisture content at the same rotational speed, at the rotary speed of 660 r/min, the centrifugal collision test was carried out on grain samples of Jingu-21 with moisture content 11.1%, 15.2%, 17.5%, 20.9% and Yuqiao-4 with moisture content 11.1%, 15.6%, 19.4% and 22.8% respectively. The relationship curve between crushing rate and moisture content is obtained by the test, as shown in figure 8.



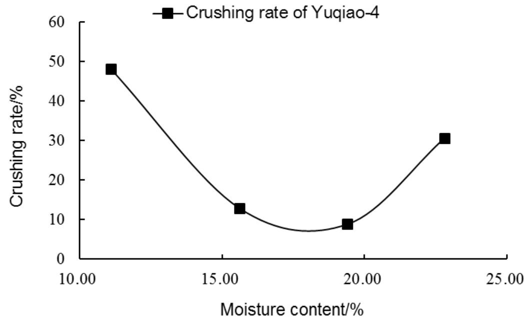


Fig. 8 - Relationship curve between crushing rate and moisture content

By fitting the relation curve in figure 8 with Matlab software, we get:

$$p_1 = 23.866x^2 - 9.3788x + 1.1555 \tag{17}$$

$$p_2 = 90.782x^2 - 32.326x + 2.9543 \tag{18}$$

where: p_1 is crushing rate of Jingu-21 at the rotary speed of 660 r/min, [%];
p_2 is crushing rate of Yuqiao-4 at the rotary speed of 660 r/min, [%];
x is moisture content, [%].

The relationship between breaking rate and moisture content is quadratic polynomial. The fitting accuracy is good (R^2 is 0.991, 0.9978 respectively).

According to the fitting formula, when the moisture content is 19.7% and 17.8%, the crushing rates p_1 and p_2 are the minimum, respectively. The test results showed that when the rotating speed of rotary table was 660 r/min, when the moisture content of Jingu-21 was 19.7%, the crushing rate was 21.9%; when the moisture content of Yuqiao-4 was 17.8%, the crushing rate was 7.1%. The test results were close to the model.

All peak voltages are recorded each time, and the collision force of millet and buckwheat at different rotational speeds is calculated according to formula (15). According to formula (12), the linear velocity of grain leaving the edge of rotary table is calculated, as shown in Table 2.

Table2

Collision force of millet and buckwheat grains under different rotating speed

Variety	**Rotary speed [r/min]**						
	120	280	380	580	660	780	910
Linear velocity of grain [m/s]	3.57	8.32	11.30	17.24	19.62	23.19	27.05
Collision force of Jingu-21[N]	3.52	5.51	10.6	12.74	14.98	16.70	18.77
Collision force of Yuqiao-4[N]	5.27	8.92	12.79	15.59	18.72	20.15	22.07

It can be seen from Table 2 that the larger the rotating speed of the rotary table, the greater the linear velocity of the grain leaving the edge of the rotary table, and the greater the collision force of the grain. Compared with the literature of Sun (*Sun et al., 2018*) and Sun (*Sun et al., 2017*): it can be seen that under the same moisture content, the collision force of crushing damage of millet and buckwheat grains under dynamic load is less than that of static load compression.

Table 1 and Table 2 show that the collision force of crushing damage is about 5.51 N, 10.6N and the linear velocity of grain is about 8.32 m/s, 11.30m/s when the moisture content is 11.1% and 20.9% respectively. The collision force of crushing damage is about 8.92 N, 12.79N and the linear velocity is about 8.32 m/s, 11.30m/s when the moisture content is 11.1% and 22.8% respectively. When the rotating speed of is 910 r/min, the linear velocity of grain is 27.05 m/s, and the crushing rate of millet grain and sweet buckwheat grain is 56.30% and 63.76% respectively. And the crushing rate of millet grain and sweet buckwheat grain with moisture content of 11.1% is 86.27% and 89.4%, respectively.

CONCLUSIONS

1. This paper designs a centrifugal collision test device for millet, buckwheat and other grains. The adjustable speed motor is directly connected to the rotary table through the spindle, which has compact structure and can reduce the loss of mechanical energy. The angle of collision baffle is adjustable and the thickness and material of the baffle can be replaced. The PVDF piezoelectric pressure sensor can accurately determine collision force. The device can be used to determine the critical collision damage force of grain and shelling force of granular materials with shells (grain diameter ≤15 mm).

2. Under the same moisture content, the higher the rotational speed, the higher the crushing rate of millet and buckwheat grains. At the same rotational speed, the crushing rate decreases first and then increases with the increase of moisture content. When the moisture content of Jingu-21 and Yuqiao-4 is 19.7% and 17.8%, respectively, the grain crushing rate is the smallest. From the anti-collision ability of grain, the optimum moisture content of threshing is between 19.7%~21% for millet,17.8%~19% for sweet buckwheat, and the optimum moisture content of centrifugal sheller is about 11%.

3. The higher the rotational speed of centrifugal rotary table, the greater the linear velocity of grain, the greater the collision force. At the same rotational speed, the collision force of millet and buckwheat is different. Under dynamic loading, the collision force of grain damage of millet and buckwheat is less than that of static load compression. The collision force of millet grain damage is about 5.51 N, 10.6 N when moisture content is 11.1% and 20.9% respectively. The collision force of sweet buckwheat grain damage is about 8.92N, 12.79N when moisture content is 11.1% and 22.8% respectively.

4. The research method and results of this article can provide theoretical basis for design and optimization of millet and sweet buckwheat combine harvester, threshing device and shelling device.

ACKNOWLEDGEMENTS

This research titled 'Design and experiment of centrifugal collision test device for millet and sweet buckwheat grain' was funded by the National Key Research and Development Plan of China (2016YFD0701801), Science and Technology Innovation Project of Shanxi Province (2020L0568) and Doctoral Research Start Project of Yuncheng University (YQ-2019020). The authors are grateful and honoured to have obtained support from the Laboratory of Agricultural Biomechanics.

REFERENCES

[1] Cao R., (2019). *Research on signal processing system of multichannel PVDF piezoelectric thin film grain loss sensor based on DSP* (基于DSP的多通道PVDF压电薄膜谷物损失传感器信号处理系统研究). [Unpublished master's dissertation]. Zhejiang University, Zhejiang/China.

[2] Chen W., (2019). *Experimental study on the mechanism of buckwheat kernel shelling and the performance of sheller based on low loss and high efficiency* (基于低损高效的荞麦籽粒剥壳机理及剥壳机性能试验研究). [Unpublished doctoral dissertation]. Inner Mongolia Agricultural University, Inner Mongolia /China.

[3] Domingos I, Bilsborrow P.E., (2021). The effect of variety and sowing date on the growth, development, yield and quality of common buckwheat (*Fagopyrum esculentum Moench*) [J]. *European Journal of Agronomy*, 2021, vol.126, 126264, United Kingdom.

[4] Du X., Ji J., Jin X., Li C., Yang X., (2018). Research on divider losses with high-speed photography for foxtail millet harvesting. *Future Generation Computer Systems*, vol.88, pp. 55-60, Henan/China.

[5] Fan C., Cui T., Zhang D., Yang L., Qu Z., Li Y., (2019). Design and test of low-damage combined corn threshing and separating device (低损伤组合式玉米脱粒分离装置设计与试验). *Transactions of the Chinese Society for Agricultural Machinery*, vol.50, issue 4, pp. 113-123, Beijing/China.

[6] Guo G., Lv X., Guo K., Dang G., (2005). Experimental study on the performance of rapeseed sheller (油菜籽脱壳机脱壳性能试验研究). *Transactions of the Chinese Society for Agricultural Machinery*, vol.36, issue 1, pp. 148-149, Shanxi/China.

[7] Hou H., Cui Q., Guo Y., Zhang Y., Sun D., Lai S., Liu J., (2018). Design and test of air-sweeping suspension velocity testing device for cleaning threshed materials of grain and oil crops (气吹式粮油作物脱出物清选悬浮速度测量装置设计与试验). *Transactions of the Chinese Society of Agricultural Engineering*, vol.34, issue 16, pp. 43-49, Shanxi/China.

[8] Huang X., Zhang W., Dang W., Zhang K., Feng S., Liu Z., Yang F., (2018). Research status and development trend of buckwheat harvester (荞麦收获机械研究现状及发展趋势). *Agricultural Machinery*, vol.850, issue 10, pp.84-90, Shanxi/China.

[9] Hyeon J., Il S., Tae G., Yong C., Duck K., Choung K., (2015). Study on performance improvement of a head-feeding rice combine for foxtail millet harvesting. *Journal of Biosystems Engineering*, vol.40, issue 1, pp. 10-18, Jeonju/Korea.

[10] Ji J., Li X., Jin X., Geng L., He Z., Li S., Pang J., (2016). Present situation, technical analysis and equipment demand of harvesting mechanization for characteristic coarse cereals (特色杂粮收获机械化现状、技术分析及装备需求). *Agricultural Engineering*, vol.6, issue 6, pp.1-3, Henan/China.

[11] Jiang N., Yi S., Zhang K., (2011). Comparative analysis of grain movement and collision for different drum speeds axial flow device (不同滚筒转速轴流装置籽粒运动和碰撞对比分析). *Transactions of the Chinese Society for Agricultural Machinery*, vol.42, pp. 48-51, Heilongjiang/China.

[12] Joshi D C, Chaudhari G V, Sood S, Kant L, Pattanayak A, Zhang K, Fan Y, Janovská D, Meglič V, Zhou M L, (2019). Revisiting the versatile buckwheat: reinvigorating genetic gains through integrated breeding and genomics approach [J]. *Planta*, vol.250, pp.783-801, India.

[13] Liang S., Jin C., Zhang F., Kang D., Hu M., (2015). Design and experiment of 4LZG-3.0 millet combine harvester (4LZG-3.0 型谷子联合收获机的设计与试验). *Transactions of the Chinese Society of Agricultural Engineering*, vol.31, issue 12, pp. 31–38, Jiangsu/China.

[14] Liang Z., Li Y., Xu L., Zhao Z., (2016). Sensor for monitoring rice grain sieve losses in combine harvesters. *Biosystems Engineering*, vol.147, pp. 51-66, Jiangsu/China.

[15] Li X., Ma F., Gao L., (2009). Dropping impact experiment on corn seeds (玉米种子的跌落式冲击试验). *Transactions of the Chinese Society of Agricultural Engineering*, vol.25, issue 1, pp. 113-116, Henan/China.

[16] Li X., Meng Y., Zhang J., Geng L., Ji J., (2018). Design and test of cleaning device for roller rubbing cylinder sieve of millet (辊搓圆筒筛式谷子清选装置设计与试验). *Transactions of the Chinese Society for Agricultural Machinery*, vol.49, issue 10, pp. 92-102, Henan/China.

[17] Li H., Xue J., Wang B., Zhang Y., Wu X., Li X., Cui Q., Yang Z., (2020). Tensile properties of foxtail millet leaf sheath, leaf and leaf collar (谷子茎秆叶鞘叶片及其结合部位的拉伸力学性能). *Transactions of the Chinese Society of Agricultural Engineering*, vol.36, issue 18, pp. 11–17, Shanxi/China.

[18] Li X., Yu Y., Geng L., Wang S., Pang J., Ji J., (2018). Study on collision test of sunflower seed (向日葵籽粒碰撞试验研究分析). *Journal of Agricultural Mechanization Research*, vol.7, issue 7, pp. 175-179, Henan/China.

[19] Lu Q., Zheng D., Liu Y., Li L., Xu B., Ye S., (2020). Problems and thoughts on mechanized harvesting technology of buckwheat in China (我国荞麦机械化收获技术问题与思考). *Agricultural Engineering*, vol.10, issue1, pp. 6-9, Shanxi/China.

[20] Lu W., Wang R., Deng Z., (2017). Development status and prospect of threshing technologies for coarse cereal (杂粮联合收获脱粒技术研究现状与展望). *Journal of Chinese Agricultural Mechanization*, vol. 38, issue 11, pp. 11-16, Henan/China.

[21] Qian Z., Jin C., Ma Z., Zhang D., (2017). Multiple frictional impact dynamics of threshing process between flexible tooth and grain kernel. *Computers and Electronics in Agriculture*, vol.141, issue 9, pp. 276-285, Jiangsu/China.

[22] Rajasekaran R, Francis N (2021). Genetic and genomic resources for improving proso millet (Panicum miliaceum L.): a potential crop for food and nutritional security [J]. *Nucleus (India)*, vol.64, pp.21-32, India.

[23] Sun J., Yang Z., Guo Y., Cui Q., Wu X., Zhang Y., (2017). Compression mechanical properties and crack formation law of millet grain (谷子籽粒压缩力学性质及损伤裂纹形成机理). *Transactions of the Chinese Society of Agricultural Engineering*, vol.33, issue 18, pp. 306－314, Shanxi/China.

[24] Sun J., Guo Y., Yang Z., Cui Q., Wu X., Zhang Y., (2018). Experimental study on biomechanical properties of buckwheat grain and viscoelastic properties of buckwheat powder (荞麦籽粒生物力学性质及内芯黏弹性试验研究). *Transactions of the Chinese Society of Agricultural Engineering*, vol.34, issue 23, pp. 287-298, Shanxi/China.

[25] Tao M., (2018). Research on mechanical properties and shelling test of oil peony seeds (油用牡丹籽粒力学特性及脱壳试验研究). [Unpublished master's dissertation]. Henan University of Science and Technology, Henan/China.

[26] Wang L., Wu B., Wu Z., Li R., Xin., (2018). Experimental determination of the coefficient of restitution of particle-particle collision for frozen maize grains. *Powder Technology*, vol.338, issue 10, pp. 263–273, Heilongjiang/China.

[27] Xu L., Li Y., Ma Z., Zhao Z., Wang C., (2013). Theoretical analysis and finite element simulation of a rice kernel obliquely impacted by a threshing tooth. *Biosystems Engineering*, vol.34, issue 23, pp. 146-156, Jiangsu/China.

[28] Xu L., Li Y., (2009). Critical speed of impact damage on a rice kernel (水稻谷粒冲击损伤临界速度分析). *Transactions of the Chinese Society for Agricultural Machinery*, vol.40, issue 8, pp. 54-57, Jiangsu/China.

[29] Zhang Y., Cui Q., Guo Y., Li H., (2019). Experiment and analysis of cutting mechanical properties of millet stem (谷子茎秆切割力学特性试验与分析). *Transactions of the Chinese Society for Agricultural Machinery*, vol.50, issue 4, pp. 146–155, Shanxi/China.