CHEMICAL ENGINEERING TRANSACTIONS
VOL. 51, 2016
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet
Guest Editors: Tichun Wang, Hongyang Zhang, Lei Tian

ISBN 978-88-95608-43-3; **ISSN** 2283-9216
DOI: 10.3303/CET1651022

Design and Experiment of Bionic Discrete Devices Based on Corn Threshing System

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To study the bionic discrete principle of beak, a discrete roller model was designed in this study. An orthogonal experiment was then conducted with different parameters and discrete roller levels. Discrete rate and damage rate are used as evaluation indexes, and the variance analysis method is used to analyze the influence of factors including discrete roller speed, differential roller speed and vertical clearance on the discrete effects of corn ear. The combination of parameters with superior performance is optimized as follows: 250 r/min discrete roller speed, 100 r/min differential roller speed and 47.5 mm vertical clearance. Based on the mechanical properties between corn kernels, the working process of discrete roller is analyzed by using high-speed photography. It is found that discrete roller has effective result for threshing corn ear and the damage is low. This research can provide a bionic thought for designing corn threshing system.

1. Introduction

Corn is an important food product in China. At present, the level of corn harvest mechanization is low because of various factors, such as the machinery, equipment and cultivation technique of farmers. Most areas are mainly dominated by manual harvesting (Zhang, 2014). In this process, a thresher is required to finish the threshing work of corn. A traditional corn sheller often uses the impact principle to achieve threshing by high-speed hitting the ear. However, the high-speed drum will cause large damage on corn kernels in the process of hitting. Thus, improving the performance of corn sheller and meeting the requirements of low damage and high threshing rates of corn kernels are the urgent concerns of corn threshing (Nkakini et al., 2007; Petkevichius et al., 2008). In recent years, bionic technology has developed rapidly, and has been explored by many researchers. Wang (Wang et al., 2015) designed and tested bionic fan blades on the basis of Seagull's wings to improve fan performance. Zhang (Zhang et al., 2015) designed a bionic spike - type sand rigid wheel with high traction performance.

The orthogonal design method has features of balanced dispersion and neat comparability. This method uses the standard orthogonal table to achieve the balanced collocation of multiple factors and multiple levels. By using a small number of representative tests, the influence of various factors on the results of the test is analyzed and the optimized combination of factors is determined. This method is often used to investigate and perform multifactorial experiments (Musmar, et al., 2014; Chen et al., 2015; Ranil et al., 2015).

In the natural world, as a result of long-term evolution, birds' beaks have an ability to disperse corn ear kernels. Given that poultry chicken belongs to Aves, their beaks can pierce corn kernels and then disperse them with low damage. The use of bionic technology to optimize the structure of corn sheller, will effectively solve the problems of low threshing rate and high damage rate of corn thresher (Li et al., 2011; Li et al., 2015). The orthogonal design method is used in the current study and to obtain the optimum combination of parameters and to investigate the effects of differential roller speed, discrete roller speed and vertical clearance between differential roller and discrete roller on the discrete effect of corn ear. Combined with mechanical characteristics of corn ear, high-speed photography is used to analyze the discrete process of corn ear. This research has practical implication for developing corn seed thresher with low-damage.

Please cite this article as: Li X.P., Wu K., 2016, Design and experiment of bionic discrete devices based on corn threshing system, Chemical Engineering Transactions, 51, 127-132 DOI:10.3303/CET1651022

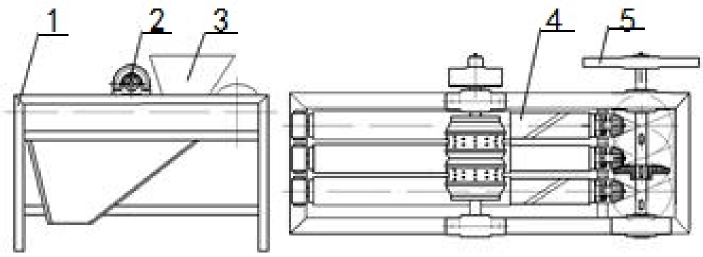
2. Biomechanical analysis of corn kernels

Kernels are connected to corn cobs via the fruit stalk. One end of the fruit stalk is connected to the seed coat, and the other end is inserted into the glume of the corn cob. When the bottom of the fruit stalk inserts into the corn cob, the glume wall will have a supporting force on the kernel. Furthermore, the area of the fruit stalk connected to the seed coat is the maximum area. When the moisture content is high, the fruit stalk has a certain toughness and elasticity. On the contrary, when the moisture content is low, the fruit stalk shrinks and becomes thin, hard and brittle.

3. Design of bionic discrete device

3.1 Structure of discrete device

To study the discrete and damage rates of corn ear in the discrete process, an experiment is conducted on a discrete test-bed with orthogonal experiment. The test-bed is mainly composed of discrete roller, differential roller, framework and drive components. To facilitate the adjustment of the roller speed, two motors are used through pulleys to pass power to the discrete roller and differential roller (Figure 1).



(a) Main view (b) Top view

1. Frame 2. Discrete roller 3. Feeding inlet 4. Differential roller 5. Belt pulley

Figure 1: Discrete test-bed of corn ear

3.2 Working principle

Corn ear is randomly fed in the feeding inlet. Considering that corn ear is not parallel to the axis of the differential roller, with the action of axial force of the front propeller of differential roller, the position of corn ear will be gradually corrected to be parallel to the axis of the differential roller. Subsequently, corn ear is pushed into a discrete space composed of the discrete roller and differential roller. Under the action of bionic beak discrete units on corn ear, the arrangement law (Li et al., 2014) between corn kernels is destroyed and parts of kernels are dispersed from the corn ear.

3.3 Design of discrete roller

The main role of a discrete roller is to undermine the arrangement law of corn ear, and loose corn kernels for subsequent threshing operations. Therefore, the main performance requirements of a discrete roller are high discrete rate and low damage rate.

(a) Discrete unit (b) Discrete roller

Figure 2: 3D model of discrete roller

Studies have found that a chicken's beak has high discrete rate and low damage rate for corn ear. In this research, a 3D scanner is used to collect the surface contour point-cloud data of a chicken's beak, which is then used to reverse the 3D model of a beak. A discrete roller is then designed. By considering the factors of optimal discrete effect and process, 12 rows of discrete units are arranged along the discrete roller circumference and intervals of 2 or 3 discrete units are arranged alternately in each row. The 3D model of discrete roller is shown in Figure 2. According to equations (1) and (2), we calculate that the length of the discrete roller is 180 mm, meanwhile, we acquire that the diameter of the discrete roller is 242 mm. The widths of two concave surfaces used to decorate the discrete units are both 53 mm.

$$L = a(\frac{Z}{k} - 1) + 2\Delta l \quad (1)$$

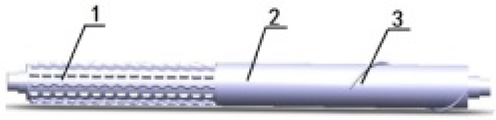
$$D = \frac{MS}{\pi} + 2h \quad (2)$$

Where, L means length of roller, mm; a means tooth trace spacing of discrete unit, mm; Z means discrete unit number; k means spiral heads number; Δl means length of discrete unit, mm; D means the diameter of the discrete roller, mm; M means rows of discrete units; S means row distance, mm; h means the height of discrete unit, mm.

3.4 Design of differential roller

The discrete roller and differential roller form a discrete space. During the discrete process, the roles of the differential roller are to support the corn ear and simultaneously rotate the ear to facilitate discrete roller acting on different parts of the corn ear.

As shown in Figure 3, the differential roller consists of spiral part, discrete part and threshing part. To reflect the discrete effect of the discrete roller, this part of the differential roller is smooth and has a length of 280 mm and diameter of 100 mm. The spiral part has length of 278mm, pitch of 250 mm, axial diameter of 100 mm and diameter of 130 mm. The length of the threshing parts is 406 mm.



1. Threshing part 2. Discrete part 3. Spiral part

Figure 3: Structure of differential roller

4. Experiment on bionic discrete device

4.1 Experimental design

Discrete roller speed A, differential roller speed B, and vertical clearance C between the discrete roller and differential roller (referred to as vertical clearance below) are selected as experimental factors. From the single-factor experiments, we conclude that the proper ranges of discrete roller and differential roller are 150-350 /r·min^{-1} and 50-150 /r·min^{-1}, respectively. Meanwhile, we acquire the proper interval of vertical clearance is 4.5 mm. Then three levels are selected each factor and are shown in Table 1. The discrete rate y_i and damage rate z_i are used as experimental index. A total of 27 experiments are conducted with L_{27} (3^{13}) orthogonal table. The experimental data are shown in Table 2.

Table 1: Factors and levels of the orthogonal experiment

Levels	Factors		
	A/r·min^{-1}	B/r·min^{-1}	C/mm
1	150	50	47.5
2	250	100	52
3	350	150	56.5

4.2 Experimental materials

Zhengdan 958 is used in the experiment. The moisture content is 11.8%. Two corn ears are selected for each group in the test.

A clairvoyance 2F01 high speed camera is used in the high speed photography experiment (University Of Science And Technology Of China), and its resolution and photo-frequency are 1128 pixels x 860 pixels and 500 frame/s, respectively. The high-speed camera is connected to a computer with an X4 3.8 GHz CPU, and 8GB RAM.

4.3 Analysis of Experimental Results

4.3.1 Discrete rate

With the discrete rate used as a testing index, analysis results of test results in Table 2 are shown in Table 3.

As shown in Table 3, factors A, B and C and interaction AB have significant effects on discrete rate. By contrast, interaction AC has no effect on discrete rate. Table 3 shows that factor C, namely, the influence of vertical clearance on test results is relatively larger. This finding can be attributed to the closer distance of the discrete roller from the corn ear, the larger contact area between the discrete roller and corn ear and the more kernels flying out of the corn ear when discrete roller speed and differential roller speed are definite. In terms of the discrete performance index, a higher value leads to better performance. Therefore, the optimal combination of $A_2B_2C_1$ is selected.

As shown in Table 3, although each single effect of factors A and B is more than the effect of interaction AB on the discrete rate, their discrete roller speed and differential roller speed have certain requirements. When the differential roller speed is determined, the discrete roller speed is not the sooner the better. As revealed from the test results of Table 2, the average discrete rate is 68.08%. In all of the 27 tests, the discrete rate of only 2 tests is less than 30%. This result indicates that the discrete roller has an excellent discrete effect on corn ear.

Table 2: Schemes and results of the orthogonal experiment

Number	A	B	$(AB)_1$	$(AB)_2$	C	$(AC)_1$	$(AC)_2$	y_i/%	z_i/%
1	1	1	1	1	1	1	1	83.94	0.13
2	1	1	1	1	2	2	2	61.54	0.19
3	1	1	1	1	3	3	3	35.39	0.16
4	1	2	2	2	1	1	1	89.54	0.12
5	1	2	2	2	2	2	2	58.71	0.18
6	1	2	2	2	3	3	3	28.53	0.11
7	1	3	3	3	1	1	1	92.21	0.3
8	1	3	3	3	2	2	2	81.25	0.2
9	1	3	3	3	3	3	3	32.44	0.19
10	2	1	2	3	1	2	3	77.34	0.12
11	2	1	2	3	2	3	1	55.35	0.21
12	2	1	2	3	3	1	2	34.41	0
13	2	2	3	1	1	2	3	95.28	0
14	2	2	3	1	2	3	1	84.91	0
15	2	2	3	1	3	1	2	92.73	0.25
16	2	3	1	2	1	2	3	97.45	0
17	2	3	1	2	2	3	1	82.59	0.21
18	2	3	1	2	3	1	2	57.34	0
19	3	1	3	2	1	3	2	90.45	0
20	3	1	3	2	2	1	3	66.57	0.27
21	3	1	3	2	3	2	1	34.94	0.11
22	3	2	1	3	1	3	2	94.16	0.08
23	3	2	1	3	2	1	3	80.88	0.24
24	3	2	1	3	3	2	1	29.93	0.16
25	3	3	2	1	1	3	2	80.54	0
26	3	3	2	1	2	1	3	78.32	0.16
27	3	3	2	1	3	2	1	41.59	0.25

Table 3: Variance analysis of discrete rate

Factors	Deviation square sums	Freedom degrees	F	Significance
A	0.076	2	4.75	*
B	0.090	2	5.625	*
AB	0.125	4	3.906	*
C	0.974	2	60.875	*
AC	0.092	4	2.875	
Errors	0.051	12		

Note: $F_{0.1}$ (2, 12) =2.81. $F_{0.1}$ (4, 12) =2.48. Empty columns and non-significant factors are chosen as error terms.

4.3.2 Damage rate

The analysis results using damage rate as the experimental index are shown in Table 4.

Table 4 shows that factors A and C have significant effects on damage rate, whereas factor B has no effect on the test results. This finding can be attributed to the supporting and pushing effects of the differential roller on

the corn ear during the discrete process. A differential roller causes friction torque on the corn ear, thus making the corn ear rotate and move backward. A larger differential roller speed leads to the faster the rotation of the corn ear and the higher dispersion of kernels from the corn ear. However, in this process, the differential roller speed will have an insignificant effect on the damage rate. A small damage rate is preferred, thus the best combination of $A_2B_2C_1$ is chosen. As observed from the test results in Table 2, in the 27 tests, the damage rate of 7 tests is 0 and the total average damage rate is 13.5%. This result indicates that the discrete roller has low damage on corn ear in the discrete process.
On the basis of the discrete rate and damage rate, the optimum combination is $A_2B_2C_1$, namely, 100 r/min differential roller speed, 250 r/min discrete roller and 47.5 mm vertical clearance.

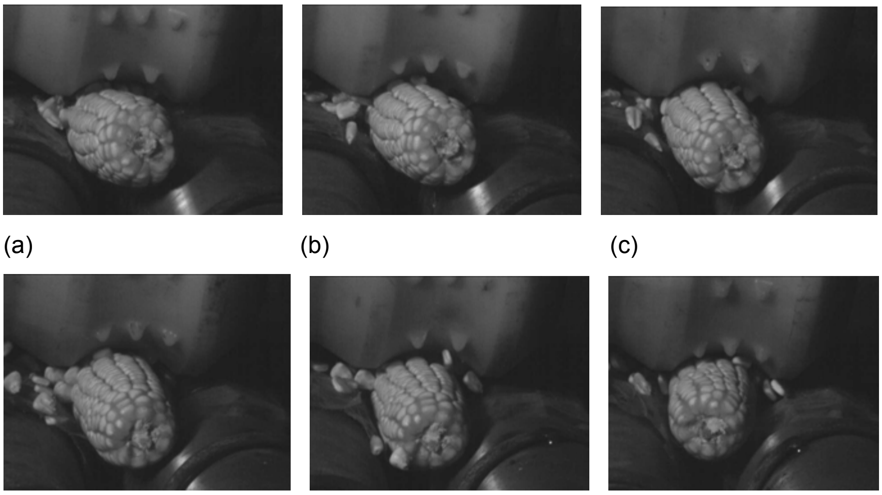
Table 4 Variance analysis of damage rate

Factors	Deviation square sums	Freedom degrees	F	Significance
A	0.035	2	2.57	*
B	0.001	2	0.14	
AB	0.017	4	0.57	
C	0.046	2	3.29	*
AC	0.033	4	1.14	
Errors	0.108	12		

Note: $F_{0.1}$ (2, 22) =2.56, $F_{0.1}$ (4, 22) =2.35. Empty columns and non-significant factors are chosen as error terms.

4.4 Process analysis of corn ear with high-speed photography

Under 100 r/min differential roller speed, 250 r/min discrete roller speed and 47.5 mm vertical clearance, the working process of a discrete roller is shown in Figure 4 on the basis of high-speed photography. Under the action of a spiral pushing device, corn ear is sent to a discrete roller below and contacts with a discrete roller. A rotating discrete roller then squeezes the corn ear and starts to disperse the corn ear kernels (Figure 4(a)). Figures 4(b) – 4(e) show that the corn ear rotates and moves backward with the action of differential roller. When the contacting area between the discrete roller and corn ear is larger, more kernels will be dispersed from the corn ear. The corn ear continues to move backward and discrete process is ended, as shown in Figure 4(f). The research has confirmed the opinion that the discrete roller has effective result on corn ear.



(a) (b) (c)

(d) (e) (f)

Figure 4: Working process of the discrete roller with high-speed photography

5. Conclusions

According to the analysis of orthogonal experiment, the optimum combination of parameters of discrete devices is obtained as follows: $A_2B_2C_1$, namely, 100 r/min differential roller speed, 250 r/min discrete roller speed and 47.5 mm vertical clearance.

High-speed photography experiments are conducted on the discrete roller with optimum parameters. Pictures show that the discrete roller significantly destroys the force balance of corn kernels. From these experiments, we come to conclude that the discrete roller can disperse corn ear with low damage.

Acknowledgments

This research is financially supported by National Nature Science Foundation of China - Henan Talent Cultivation Joint Foundation (U1204514).

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