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Full Length Research Paper

Modeling and experiment to threshing unit of stripper combine

Xu Lizhang* and Li Yaoming

Key Laboratory of Modern Agricultural Equipment and Technology, Ministry of Education and Jiangsu Province, Institute of Agricultural Engineering, Jiangsu University, Zhenjiang 212013, China.

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The aim of this study was to establish the mathematical models to axial threshing unit of stripper combine harvester. The exponential distribution model of the un-threshed grain $T_u(z)$, free grain $T_f(z)$ and cumulative gain $F(z)$ along the axial threshing drum $z \in [0, L]$ was obtained. The loss of separation L_f was the free grain which had reached the end of the threshing unit but still not separated. On the designed testing equipment, experiments of threshing performances were conducted with the different feed rates and drum rotator speeds for the rice stripped mixtures. Experimental results showed that the distribution of the cumulative separated gain was in agreement with the simulation. The results were very useful for practical analysis of grain separation and damage as well as for threshing unit design and process optimization.

Key words: Stripping, combine harvester, threshing unit, model, experiment.

INTRODUCTION

The stripper combine is combined with a stripper header. And the basic concept of the stripper header is that a rearwards rotating rotor fitted in the front of the header is fitted with 6 to 8 rows of stripping fingers that strip grain from the crop as the combine moves the head forwards while it spins backwards (Price,1993; Jiang et al., 2001). The speed of the rotor can be varied according to crop conditions. Those stripped by stripping fingers was called the stripped mixtures, which include the free grain, the un-threshed grain and some straws etc. For this reason, characteristic of the stripped mixtures which was fed into the threshing unit of the stripper combine through the feeder house was quite different from the material fed into the threshing unit of conventional combine harvester.

A scientific model which can describe the threshing process is extremely important to study threshing unit. Based on the view of mechanics, Trollope (1982) deduced a set of differential equations which describe the threshing process, but it is difficult to apply.

On the assumption of the rule of threshing process, which meets the qualification of exponential distribution, Huynh (1982) established a mathematical model, however, it is too simple and experiential, and it has great differences with the actual situation. Taking into account the parameters of threshing process, and properties of gain, a rather nice probability model of the threshing cylinder with rasp bar was published (Wan et al., 1990; Zhou et al., 1998; Yin, 1999).

Miu (2002 a, b) presented a more detailed model of the axial threshing unit of the conventional combine harvester, but it is not completely suitable for the threshing unit of stripper combine. Specific objectives of the work reported in this study were to: (1) establish a mathematical model for describing the threshing process; (2) perform experimental studies on the designed equipment for threshing performance; (3) simulation by computer on the mathematical model.

Model development

As shown in Figure 1, a threshing separation unit is in common use in the stripper combine harvester. The sign

*Corresponding author. E-mail: lzxu1979@gmail.com. Tel: +86-0511-88797214-219. Fax: +86-0511-88780175.

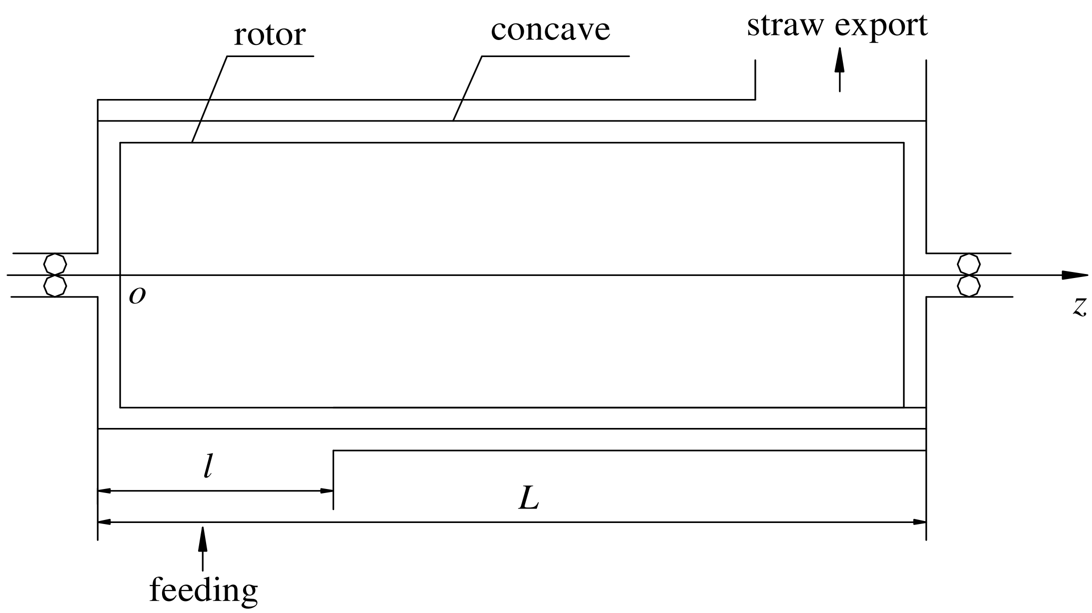

Figure 1. Schematic diagram of axial threshing unit.

"l" denotes the breadth of the entrance of the unit and "L" denotes the length of the threshing platen. Taking the point of intersection between the axial line of the platen and the side face of the entrance as the origin, the central axis of platen is defined as the z axes and the direction of axial movement of the grain is set for the plus direction of the z axes.

Assume that the feed rate of the mixture is constant; the mass of the mixture fed into the threshing unit per second is 1, then:

$$q_s(z) = \frac{z}{l}(k_1 + k_2) \tag{1}$$

Where, $q_s(z)$ is the mass of grain fed into the threshing unit per second over the interval [0,z], $z \in [0,l]$; k_1 is the percentage of the free grain, which has been threshed but not separated, in the total mass of the mixture and k_2 is the percentage of the un-threshed grain, which has not been threshed, in the total mass of the mixture.

Experimental results shows that the mixture in threshing space includes the free grain (60 to 70%), the un-threshed grain (15 to 25%) and the straw (about 10 to 20%). Therefore, the threshing process of the rice stripped mixtures includes two parts. One, the un-threshed grain are threshed, the other is the free grain separated form the concave during screwing with the rotator.

Development of the model is based on the following assumptions: (1) the probability of grain threshed and separated during the threshing space is equal in the plane through the arbitrary point of the z axis; (2) within the region from z to z+Δz, the probability of threshing for the un-threshed grain is in direct proportion to the amount of the un-threshed grain. And the proportion coefficient, named as u_1, is related to the parameters, such as the rotator speed, the cylinder-concave clearance, the structure of concave and the properties of the grain etc; (3) within the region z to z+Δz, the probability of separating form the concave for the free grain is in direct proportion to the amount of the free grain. And the proportion coefficient, named as u_2, is also related to the parameters such as the rotator speed, the cylinder-concave clearance, the structure of concave and the properties of the grain etc.

According to assumptions (1) and (2), if Δz ->0, then:

$$p_1(z) = u_1[1 - P_1(z)] \tag{2}$$

Where, $p_1(z)$ is the probability of grain threshing at a z point and $P_1(z)$ is the mass of the threshed grain within the region from 0 to z, So:

$$P_1(z) = \int_0^z p_1(s)ds \tag{3}$$

It can be obtained as follows:

$$p_1(z) = u_1 e^{-u_1 z} \tag{4}$$

Similarly, it is known:

$$p_2(z) = u_2 e^{-u_2 z} \quad (5)$$

Where, $p_2(z)$ is the probability of free grain separating out of the concave at z point; At $z \in [0, l]$ is the mass of the un-threshed grain is equal to subtraction of the threshed mass from the fed-in mass:

$$T_{u1}(z) = k_2 \frac{z}{l} - k_2 \frac{z}{l} \int_0^z u_1 e^{-u_1 s} ds = k_2 \frac{z}{l} e^{-u_1 z} \quad (6)$$

Where, $T_{u1}(z)$ is the mass of the un-threshed grain at $z \in [0, l]$.

Similarly, when $z \in [l, L]$, the equation can be expressed as follows:

$$T_{u2}(z) = k_2 - T_{u1}(l) \int_0^z u_1 e^{-u_1(s-l)} ds = k_2 e^{-u_1 z} \quad (7)$$

Where, $T_{u2}(z)$ is the mass of the un-threshed grain; $z \in [l, L]$.

If z= L, then:

$$L_t = T_{u2}(L) = k_2 e^{-u_1 L} \quad (8)$$

Where, L_t is the loss of the un-threshed.

According to the probability theory, the probability of grain separation is equal to the convolution of the probability of the un-threshed grain threshing and the probability of the free grain through which the concave occurs (Miu, 2002b). As $z \in [0, l]$:

$$f_1(z) = k_2 \frac{z}{l} p_1(z) * p_2(z) + k_1 \frac{z}{l} p_2(z) = k_2 \frac{u_1 u_2}{u_1 - u_2} \frac{z}{l} (e^{-u_2 z} - e^{-u_1 z}) + k_1 \frac{z}{l} u_2 e^{-u_2 z} \quad (9)$$

Where, $f_1(z)$ is the probability of grain separation; $z \in [0, l]$.

Integrate:

$$F_1(z) = \frac{k_2}{u_1 - u_2} \frac{z}{l} [u_1(1 - e^{-u_2 z}) - u_2(1 - e^{-u_1 z})] + k_1 \frac{z}{l} (1 - e^{-u_2 z}) \quad (10)$$

Where, $F_1(z)$ is the cumulative mass of the separating grain; $z \in [0, l]$.

Similarly, when $z \in [l, L]$:

$$F_2(z) = \frac{k_2}{u_1 - u_2} [u_1(1 - e^{-u_2 z}) - u_2(1 - e^{-u_1 z})] + k_1(1 - e^{-u_2 z}) \quad (11)$$

Where, $F_2(z)$ is the cumulative mass of the separated grain; $z \in [l, L]$.

The grain of the rice stripped mixtures which fed into the threshing unit finally is divided into three parts: the un-threshed grain, the free grain and the separated grain. Hence:

$$\begin{cases} T_{u1}(z) + T_{f1}(z) + F_1(z) = \frac{z}{l}(k_1 + k_2) & (z \in [0, l]) \\ T_{u2}(z) + T_{f2}(z) + F_2(z) = k_1 + k_2 & (z \in [l, L]) \end{cases} \quad (12)$$

Where, $T_{f1}(z)$, $T_{f2}(z)$ are the free grain corresponding to different positions z over the rotor length.

Hence:

$$\begin{cases} T_{f1}(z) = \frac{z}{l}[k_2 \frac{u_1}{u_1 - u_2}(e^{-u_2 z} - e^{-u_1 z}) + k_1 e^{-u_2 z}] \\ T_{f2}(z) = k_2 \frac{u_1}{u_1 - u_2}(e^{-u_2 z} - e^{-u_1 z}) + k_1 e^{-u_2 z} \end{cases} \quad (13)$$

The free grain which has reached the end of the threshing unit but still not separated is called the loss of separation:

$$L_f = T_{f2}(L) = k_2 \frac{u_1}{u_1 - u_2}(e^{-u_2 L} - e^{-u_1 L}) + k_1 e^{-u_2 L} \quad (14)$$

Where, L_f is the loss of separation.

MATERIALS AND METHODS

Experimental equipment

The testing equipment of axial threshing unit includes rice stripped mixtures conveyor, feeding unit, threshing unit, data acquisition and control system etc., as shown in Figure 2. The rice stripped mixtures conveyor, feeding unit and threshing unit are driven by different electromotor whose rotator speed are controllable. The structural parameters such as the cylinder-concave clearance, height and screwing angle of the oriented board on the cover

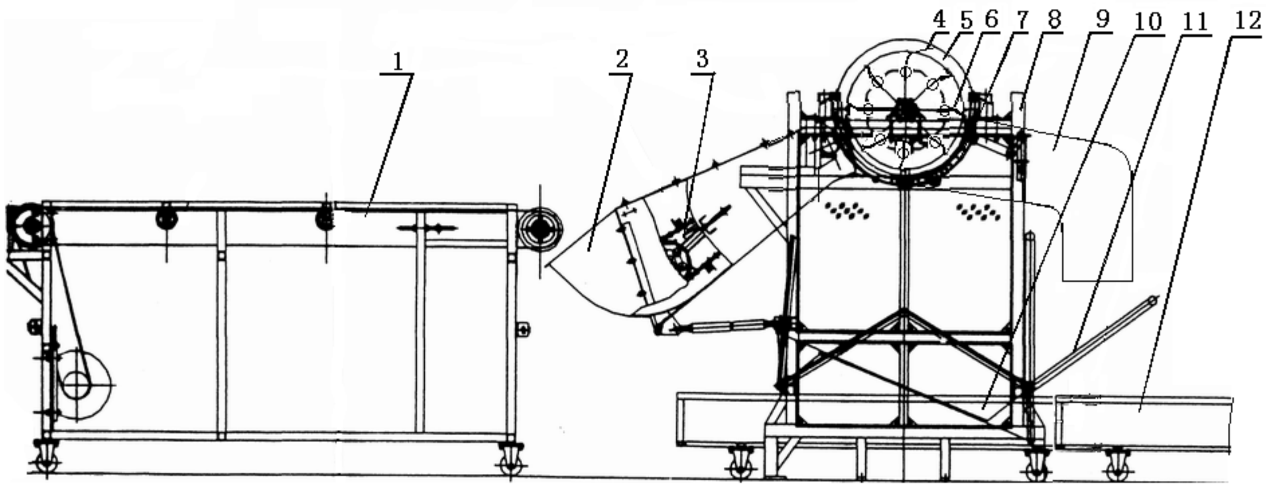

Figure 2. Schematic on testing equipment of axial threshing unit. 1, stripped mixture conveyor; 2, intakes; 3, feeding chain; 4, swath deflector; 5, threshing drum cover; 6, threshing drum; 7, separation concave; 8, frame; 9, straw outtake; 10, grain box; 11, valve handle; 12 straw boxes.

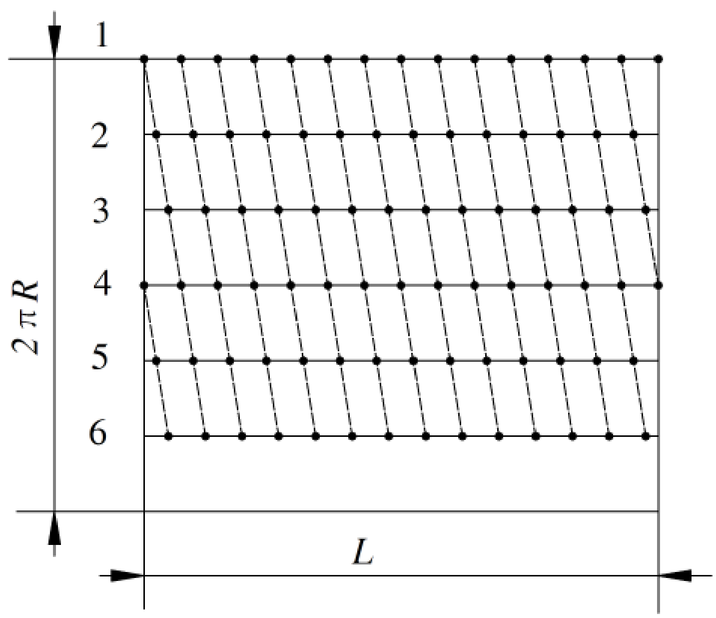

Figure 3. Distribution of spike tooth on threshing drum.

threshing element are adjustable. The sensor is installed to inspect the rice stripped mixtures conveyor speed, while sensors of rotate speed and torque are installed on the axis of feeding chain wheel and threshing drum. The side boards consist of transparent glass, so it is convenient to observe movements of grain in the test device (Xu, 2003).

In order to keep the environment of field, structure and motion parameters suitable, the testing are similar to the 4LGT-150 stripper combine harvester in marketing. Variety: late japonica rice; thousand grain weight: 29.4 g; mass percentage of the free grain in the rice stripped mixtures: 65%; mass percentage of the un-threshed grain in the rice stripped mixtures: 20%; mass percentage of the straw in the rice stripped mixtures: 15%; moisture content of mixture: 37.2%; moisture content of grain: 24.3%; moisture content of straw: 61.2%; rotor radius: 297mm; entrance breadth (l):480 mm; whole rotor length (L):1580 mm; threshing element: spike tooth (distribution of spike tooth is shown in Figure 3); number of tooth bar: 6; cylinder-concave clearance: 8 mm; concave style: grid concave; concave enveloping angle: 220°; conveyor speed: 1 m/s; feeding chain wheel rotate speed: 466 r/min.

Experimental methods

The whole length of threshing rotor was divided into 10 testing zones, the entrance breadth 5 equally uniforms and the rest 5 equally divvied, as shown in Figure 4. The testing arrangements

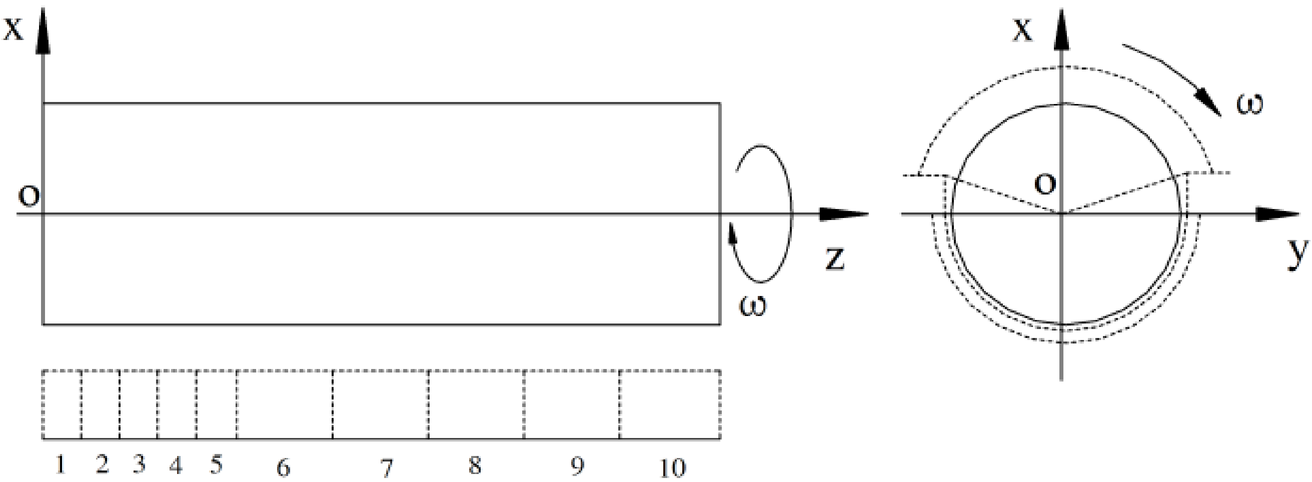

Figure 4. Distribution of the testing zones.

Table 1. Experimental result of the threshing unit.

Serial number	Feed rate /kg.s^{-1}	Rotator rotate speed /r.min^{-1}	Separation loss rate/%	Un-threshed loss rate/%	Total loss rate/%
1	1.5	750	0.154	0.304	0.458
2	1.5	850	0.158	0.226	0.384
3	1.5	950	0.161	0.172	0.333
4	1.8	750	0.206	0.544	0.75
5	1.8	850	0.212	0.376	0.588
6	1.8	950	0.223	0.208	0.431
7	2.0	750	0.328	0.51	0.838
8	2.0	850	0.344	0.448	0.792
9	2.0	950	0.338	0.244	0.582

were carried out on three feed rates and three rotate speeds, as listed in Table 1. Each group repeats 3 times.

Before the test begin, the rice stripped mixtures of certain mass are uniformly placed on the conveyer 30 m long. In the process of test, the rice stripped mixtures were fed into the threshing space, in which the un-threshed grain is threshed and the free grain is separated through feeding chain. Grains from the concave grate drop into the testing zone of the grain box. The ejection from the threshing unit falls into the straw box with the straw, from which the un-threshed loss and the separation loss can be obtained.

Separation loss rate $L_s = \frac{T_s}{\mathrm{W}} \times 100\%$ (15)

Where, T_s is the mass of the un- separation grain and W is the mass of the total grain including un- separation grain and un-threshed grain.

Un-threshed loss rate:

$$L_t = \frac{T_u}{\mathrm{W}} \times 100\% \quad (16)$$

Where, T_u is the mass of the un-threshed grain.

Total loss rate:

$$L_{to} = L_t + L_s \quad (17)$$

RESULTS AND DISCUSSION

Experimental analysis

The experimental results on the rice stripped mixtures to the threshing unit are listed in Table 1 with three different feed rate and three levels of the rotate speeds of the threshing drum.

It is known from the table that: (1) at the same feed rate, rotate speed of threshing drum has an obvious effect to the loss rate of un-threshed and the higher the rotate speed is, the smaller the un-threshed loss rate. But it is unobvious to the loss rate of separation; (2) on the condition that other parameters do not change, the feed

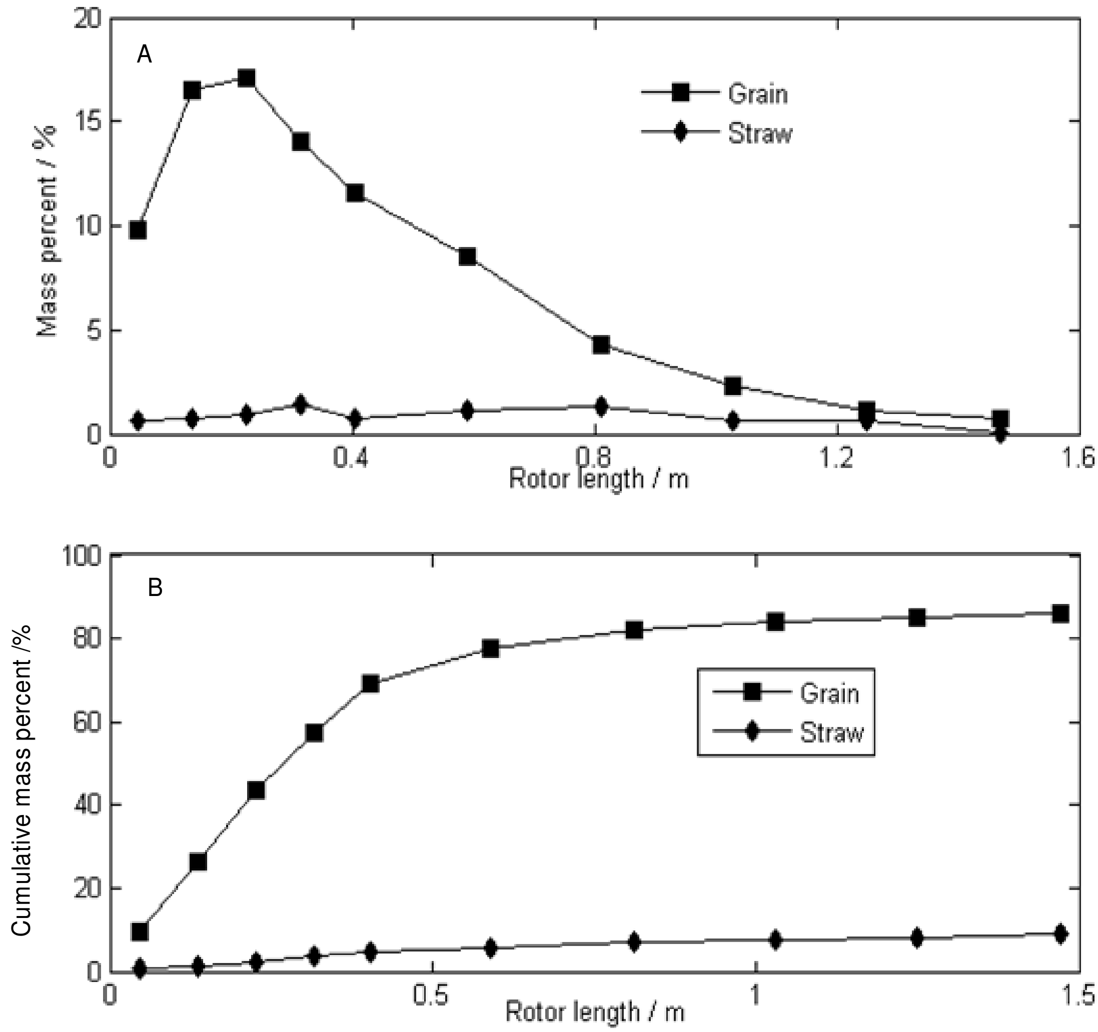

Figure 5. Axial distribution of grain and straw.

rate of the rice stripped mixtures into the threshing unit has a remarkable effect on the un-threshed loss rate and separation loss rate and the larger the feed rate is, the bigger both the loss rate increase accordingly.

As feed rate is 1.8 kg/s and rotate speed of threshing drum is 850 r/min, the axial distribution of the grain in testing zone is shown in Figure 5. It can be deduced from the figure that: (1) as shown in Figure 5a, the grain separated from the concave grate increases rapidly in width of the feeding entrance and reaches maximum at the center point of the entrance, then reduces fast. The curve of grain falls slowly in the rest length, which tends to zero by the end of the threshing drum axis. It means that the loss of grain is little. The distribution of the straw separated from the concave grate is average along the whole length; (2) it is known from Figure 5b that, about 70% of the grain has been separated during width of the feeding entrance (1/3 whole length). If no measure is adopted, the load to cleaning must be uneven, so that the cleaning performances become worse.

Simulation analysis

As feed rate is 1.8 kg/s and rotate speed of threshing drum is 850 r/min according to the test, it can be observed that the un-threshed loss rate is 0.376% and the separation loss rate is 0.212%, then solving equation (8) and (14), it is obtained as follows:

$$u_1 = 2.5151;\ u_2 = 6.994. \qquad (18)$$

Where, l = 480 mm; L = 1580 mm; k_1 = 65% and k_2 = 20%.

Using equations (1), (6), (7), (10), (11) and (13), simulations are conducted by computer, as shown in Figure 6. It is known from the simulation that: (1) the cumulative mass of the separated grain increased rapidly as exponential curve during the entrance of the mixture, after which, curve of the mass went gentle gradually. In

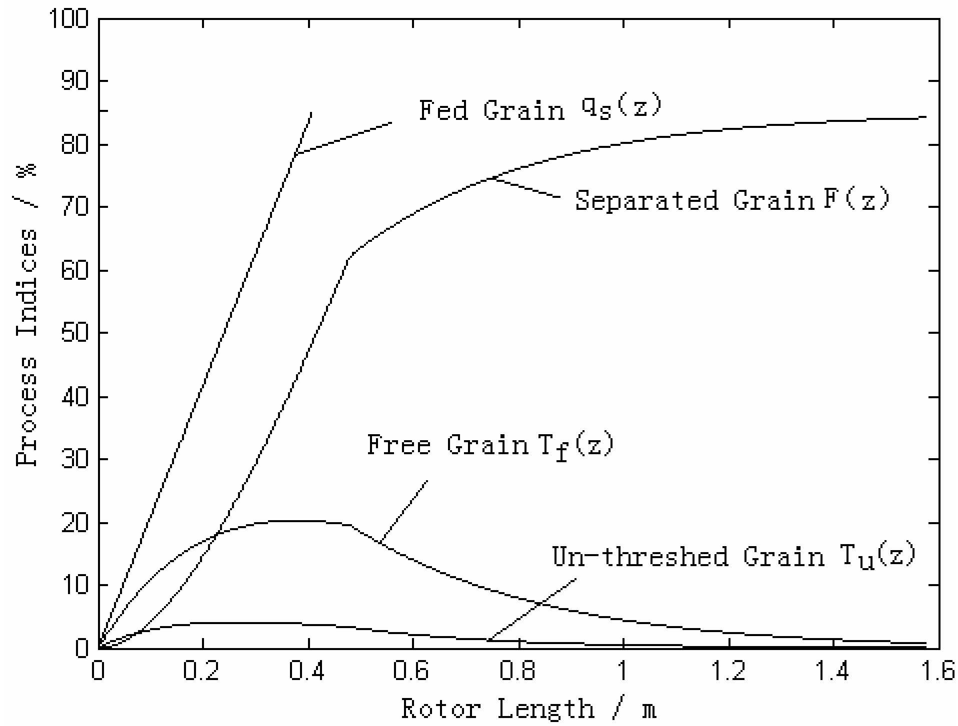

Figure 6. Variation of the indices of threshing process.

the whole drum, nearly 70% of the grain has been separated in the anterior part of one third of the whole length, which is in agreement with the experimental results, as shown in Figure 5b; (2) at first, the mass of the free grain in the threshing space increases continuously and it reaches maximum at the end of the feeding entrance, then it decreases gradually. By the end of the threshing drum, the value of the free grain mass is called the loss of separation; (3) comparatively, the mass of the un-threshed grain in the threshing space changes slowly, it also increases firstly and then reduces, which only accounts for 20% in the rice stripped mixtures. So, it seems small comparatively. By the end of the threshing drum, the value of the un-threshed grain mass is called the loss of un-threshed.

Conclusion

In this study, a mathematical model of threshing unit with axial feeding of the stripper combine is established with the method of probability and simulations are also conducted. The simulations show the variation of the indices of threshing process along threshing drum axis, including un-threshed gain, free gain and cumulative separated gain. On the self-designed testing equipment, experiments on threshing performance with different feed rate and drum rotator speed are conducted for the rice stripped mixtures. Experimental results show that, the distribution of the cumulative separated gain is in agreement with the simulation. It is known from the test that about 70% of grain is separated in the width of feeding entrance, so the measures must be taken to make the cleaning loads even. It is helpful for a better understanding of threshing processes in axial units and significant for the design of the threshing unit of the stripper combine.

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