Double-objective optimization simulation and orthogonal experiment of shredding roller for silage machine

Yingshuai Jiang¹, Guoping Li¹ and Xiangfang Zhang¹

¹ School of Mechanical Engineering University of Jinan, Shandong Province, 250022, China

*Corresponding author’s e-mail: 727515509@qq.com

Abstract. At present, the main factor affecting the quality of the silage of the silage machine is the shredding roller. Therefore, a theoretical model based on single-page hyperboloids and a shredding roller with a herringbone arrangement are designed. Then, the theoretical analysis of each key parameter was carried out. The consumption of energy and throwing height of the shredding roller can be targeted, and the orthogonal simulation was performed on each parameter combination. The optimal parameter combination was obtained as the rotational speed of 1426r/min, the rake angle is 53°, the sliding-cutting angle is 8°, and the influence of each factor and level on the consumption of energy and the throwing height is analyzed successively. The verification of experiment that the shredding loss rate was reduced by 5% compared with the pre-optimization, the optimized of broken stems is 25% higher than pre-optimization, the throwing height was 30mm higher than the pre-optimization, and the consumption of energy was reduced by 3.1% compared with the pre-optimization. The optimized of objective was within the prescribed range.

1. Introduction

The shredding roller is a key part of the design of the whole machine. According to research, shredding performance is affected by many factors such as the positional relationship between the moving knives and the fixed knife, the structural parameters of the moving knives (sliding-cutting angle, knife edge angle) and installation angle, the shape of the knife and the rotation speed of the shredding roller. The common shredding roller mainly include plane table-cutter, helical hob cutter, and slanting installing cutter with straight edge.

Xianglan Pu [1] et al, studied the energy of straight-edged oblique-mounted shredder to shred forage, selecting the lowest energy of consumption is the optimization goal, the energy of From the experiment we can see that the sliding-cutting is more labor-saving than cutting consumption was reduced and the performance was improved under the constraint condition; Yongqing Liu [2] et al, found out the optimal combination of sliding-cutting angle, fixed cutter configuration height and speed of roller by carried out an experimental study on the shredding energy of the helical hob cutter in cutting hay under different working conditions; Wu Qiaomei [3] et al, theoretically analyzed the parameters of the plane table-knife shredding conveyor, finite element analysis of the moving knives, and optimized size structure of moving knives; Zhao Xuelin [4] studied the stem shredding recovery device and designed a self-sharpening blade model.

According to the above analysis, only the power has been studied. The height of the throwing determines the parameters of the shredding roller. Therefore, a double-objective optimization analysis of
power and throwing height was proposed, thus, the most suitable parameter combination of the shredding roller was obtained.

2. Establishment of a single-leaf double-curved straight-knife oblique-mounted shredding roller model

The installation of straight-edged oblique-loaded cutter is tilted, and the track is a single-leaf hyperboloid when the knife edge rotates around the rotary axis. As shown in Fig. 1, it can be seen that the edge line of AB is rotated around the rotation axis of OZ. The equation is

\[
\frac{x^2 + y^2}{a^2} - \frac{z^2}{c^2} = 1
\]

(1)

In formula (1), \(a\) is the real half-axis of single-leaf double-curved; \(c\) is the virtual half-axis of single-leaf double-curved.

In Fig. 1, taking the above-mentioned single-leaf hyperboloid with the section \(x=a\), two straight lines can be obtained, and the equation is:

\[
\begin{align*}
 x &= a \\
 z &= cy/a \\
 z &= -cy/a
\end{align*}
\]

(2)

Fixed knife have two mounting positions to achieve equal gap cutting: One is a straight line that coincides with the edge of the moving knives at a certain rotation angle, the other is the conjugate straight line of the moving edge line at a rotation angle[5], but the installation of fixed knife with straight edge and the adjustment of cutting gap will be more difficult, so the fixed knife adopts straight edge and is installed horizontally.

2.1 Push angle and friction angle

As shown in Fig. 3, the moving knives edge is AB, fixed knife edge is CD, the angle between the cutting edge line and the fixed cutting edge line is the pushing angle, it is closely related to forage type and material of moving knives and fixed knife. Due to the horizontal installation of the fixed knife, the pushing angle is unchanged during the rotary cutting process[6]. The angle between the material and the knife is \(\delta\). If \(\psi \geq 28^\circ\), the resultant force \(F\) pushes the material outward along the knife when cutting. If \(\psi \leq 28^\circ\), the resultant force \(F\) is inward, the material must be stable and the force \(F\) needs to be inward.
The pressure of the knife to forage is $N_1$, the friction is $f_1N_1$. The pressure of moving knives to forage is $N_2$, the friction is $f_2N_2$. The condition of stable cutting is:

$$f_1N_1 \geq N_2\sin x - f_2N_2\cos x$$  \hspace{1cm} (3)

$$N_1 = f_2N_2\sin x + N_2\cos x$$  \hspace{1cm} (4)

$$f_1 = \tan\delta_1, f_2 = \tan\delta_2,$$

the formula is simplified as follows:

$$\tan x\psi \leq \tan (\delta_1 + \delta_2)$$  \hspace{1cm} (5)

In the formula, $\psi$ is the pushing angle; $\delta_1$ is the friction angle of the material and the moving knives edge; $\delta_2$ is the friction angle between the material and the fixed knife edge.

The dynamic friction coefficient of moving knives, fixed knife and silage corn with water content of 65% is 0.45, and the materials of moving and fixed knife are same. According to the above formula, so that the maximum pushing angle of cutting green corn is 48°.

2.2 Advantages and calculations of sliding-cutting angle

As shown in Fig. 4, AB is the moving edge line, $v$ is the speed of moving knives, and $v$ can decompose into the velocity $v_n$ that perpendicular to the cutting edge and the velocity $v_l$ that parallel to the cutting edge. $v_n$ and $v_l$ are called cutting speed and sliding-cutting speed, the ratio of the above two speeds is tangent, from Fig. 4 we can see that $\tan \tau = \frac{v_l}{v_n}$, called the sliding-cutting coefficient, $\tau$ is called the sliding-cutting angle, when $\tau > 0$ and does not exceed the moving edge and the friction angle $\delta$ of the stem is called slip cutting. From the above analysis, it is known that for a single-leaf hyperbolic flat knife-type shredder, a suitable sliding-cutting angle needs to satisfy the condition: $0 < \tau < \delta$.

2.3 Moving knives installation Rake angle

In order to reduce the friction between the front plane of the knife and the cutting surface, the installation of the knife should have a gap angle. The installation gap angle of the knife is the normal angle between the moving knives and the cutting plane. As can be seen from the Fig. 5, the rake angle $\varphi$, the knife angle $\beta$ and the installation gap angle $\gamma$ of the knife have the following relationship:

$$\varphi = 90^0 - \beta - \gamma$$  \hspace{1cm} (6)
It can be seen that the pre-cutting angle determines the height of the forage, if the rake angle too large, the throwing height will not be reached, and the silage can’t be throwing into the crushing device for crushing operation; on the contrary, if the knife installation gap angle γ is too large, the corresponding cutting rake angle φ becomes small, which increases the windward area of the material, thereby increasing the energy of consumption. Therefore, in the case of satisfying the throwing condition, a smaller installation gap angle should be selected as much as possible. In general, γ ≤ 48° ~ 58°.

3. ORTHOGONAL EXPERIMENT TO DETERMINE THE PARAMETERS OF THE SHREDDER ROLLER

From the above analysis, the factors affecting consumption of energy mainly include sliding-cutting angle, rake angle and speed. From the above analysis, the factors affecting consumption of energy mainly include sliding-cutting angle, rake angle and speed. At the same time, these factors also affect the height of the centrifugal transfer of the shredding roller. According to the design requirements of the whole machine, the speed range is from 1200 to 1700 r/min[7], there are two objectives of throwing height and consumption of energy, a combination of low consumption of energy and higher throwing height is needed, the data is shown in the table 1.

| Table 1. Three Factors and Three Levels |
|-----------------------------------------|
| Factor | Rotational Speed A (r/min) | Slip angle B (°) | Rake angle C (°) |
| Level  |                        |               |                |
| 1      | 1206                    | 8             | 48             |
| 2      | 1426                    | 16            | 53             |
| 3      | 1646                    | 24            | 58             |

In order to save cost, and get the best parameter combination quickly and accurately, orthogonal experiment with the $L_9(3^4)$, the last column was deleted[8], The test data was obtained through simulation analysis, as shown in Table 2.

| Table 2. Orthogonal Experimental |
|----------------------------------|
| Times | Factor | 1 | 2 | 3 | Results of each objective |
|       | A     | B | C | Cutting force of peak(N) | Speed of peak (m/s) |
| 1     | 1     | 1 | 1 | 8331                        | 98                  |
| 2     | 1     | 2 | 2 | 8796                        | 86                  |
| 3     | 1     | 3 | 3 | 9797                        | 81                  |
| 4     | 2     | 1 | 2 | 7196                        | 134                 |
| 5     | 2     | 2 | 3 | 7396                        | 106                 |
| 6     | 2     | 3 | 1 | 8872                        | 136                 |
| 7     | 3     | 1 | 3 | 8721                        | 99                  |
| 8     | 3     | 2 | 1 | 11196                       | 137                 |
| 9     | 3     | 3 | 2 | 10416                       | 126                 |

| Table 3. Double-Objective Range |
|----------------------------------|
| Objective | Cutting force of average | Speed of average |
| Range     |                          |                    |
| $K_1$     | 26924                    | 24248               | 28399               | 265 | 318 | 371 |
| $K_2$     | 23464                    | 27388               | 26408               | 376 | 329 | 346 |
| $K_3$     | 30333                    | 29085               | 25914               | 362 | 343 | 286 |
| $k_1$     | 8975                     | 8083                | 9466                | 88  | 106 | 113 |
| $k_2$     | 7821                     | 9129                | 8803                | 125 | 110 | 115 |
| $k_3$     | 10111                    | 9695                | 8638                | 121 | 114 | 95  |
| Range     | 2290                     | 1612                | 828                 | 37  | 8   | 20  |
| Excellent solution | $A_2$ | $B_1$ | $C_3$ | $A_2$ | $B_3$ | $C_2$ |


The effect of speed A on each objective, as seen from Table 3, for energy of consumption, it is one of the most important factors about energy consumption. It is best to take the second level. For the throwing height, although the range of the speed is the smallest, it is also taken the second level is the best, so for both indicators, 1426 is the best speed for double-objective.

The influence of the sliding-cutting angle B on each objective, the forage of throwing height is reflected by the speed obtained after the forage is cut off. As seen from Table 3, for energy of consumption, the range is less than the speed, but much larger than the rake angle, it is best to take the first level. For the throwing height, the range is the smallest, it shows that the effect of this factor on the throwing height is the smallest. As seen from Fig. 6 that the first level is not too bad for the sliding-cutting angle. For the two objectives, the best sliding-cutting angle is 8.

The influence of the rake angle on each objective, as seen from Table 3, for energy of consumption, the difference of the rake angle is the smallest, that is, the influence of consumption of energy is the smallest, and the level of 3 is the best. For the throwing height, the range of the front angle is between the speed and the sliding-cutting angle, the second level is best. For energy of consumption, the effect of the rake angle is minimal. It can be seen from Fig. 6, taking the second level of energy of consumption is not too high, so, it is better to take the second level.

Through a comprehensive analysis of the impact of various factors on each objective, a better experiment plan is:
- \( A_2 \): speed, second level, 1426;
- \( B_1 \): sliding-cutting angle, first level, 8;
- \( C_2 \): rake angle, first level, 53.

4. Verification of experiment

In order to verify whether the optimal combination of parameters meets the requirements, the analysis results were experimented. The indicators of experiment are:

4.1. Rate of Shredding loss

Taking 1Kg of shredded green corn stems. In the shredded stems that less than 20mm in length and larger than 35mm are considered to be losses. The formula is:

\[
 z_1 = \frac{x_1}{x_2} \times 100\% \tag{7}
\]

In the formula, \( z_1 \) is the rate of shredding loss; \( x_1 \) is the number of broken stems whose length is not between 20-30 mm; \( x_2 \) is total number of samples.

4.2. Average of cut length

Measuring the length and quantity of the sample and calculate the average.

4.3. Throwinging height

The detection of the throwing height needs to be measured separately before assembling the machine, place the gauze over the shredding roller, and adjust the height of gauze, then, observing the gauze whether have broken stems.
4.4. Energy of consumption ratio

The energy of the working device is derived from the engine, and is calculated by the distribution ratio of each working member. The formula is:

\[ N = qv^2/(1 - f) \times 10^{-3} \]  

In the formula, the \( N \) is power, the unit is Kw; the \( q \) is feed quantity, the unit is Kg/s; the \( v \) is circumferential speed, the unit is m/s; the \( f \) is coefficient of comprehensive friction.

Three repeated experiment were carried out to compare the parameters before optimization, the pre-optimization speed is 1646 r/min, the sliding-cutting angle is 24°, and the rake angle is 48°, the experiment results are shown in Table 4.

Table 4. Optimal combination experiment result

| Parameter             | Shredding loss rate (%) | Broken stems length (mm) | Throwing height (mm) | Energy of consumption ratio (%) |
|-----------------------|-------------------------|--------------------------|----------------------|---------------------------------|
| Theoretical value     | 3                       | 25                       | 630                  | 15                              |
| Value of experiment   | 3                       | 24.43                    | 630                  | 15.9                            |
| Pre-optimization value of experiment | 8                       | 18.16                    | 600                  | 19                              |

5. CONCLUSION

The experiment of double-objective orthogonal simulation is a very efficient experimental method. Analyzed the reasons of poor forage quality and improved the structure of the shredding roller, and on the basis of this structure, the energy of consumption and the throwing height are taken as the objectives, and the parameters are optimized by the experiment of double-objective orthogonal simulation. The results of experiment proved the simulation results fulfill the design requirements, and the following conclusions are drawn: the shredding loss is reduced by 5% compared with the pre-optimization, and the consumption of energy is reduced by 3.1% compared with the pre-optimization, the throwing height is 30mm higher than before optimization.

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