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Design and Experiment of Bionic Straw-Cutting Blades Based on Locusta Migratoria Manilensis

Jinpeng Hu 1, Lizhang Xu 1, Yang Yu 1,*, Jin Lu 1, Dianlei Han 1, Xiaoyu Chai 1, Qinbao Wu 1 and Linjun Zhu 2

1 College of Agricultural Engineering, Jiangsu University, Zhenjiang 212013, China; hujinpeng2018@gmail.com (J.H.); justxlz@ujs.edu.cn (L.X.); jinLu@ujs.edu.cn (J.L.); handianlei@ujs.edu.cn (D.H.); xfpaxy@ujs.edu.cn (X.C.); 18652685198@163.com (Q.W.)
2 Jiangsu World Agricultural Machinery, Danyang 212300, China; goodzhulinjun@163.com
* Correspondence: author: yu_yang@ujs.edu.cn

Abstract: Aimed at addressing the problems of the existing straw choppers on combine harvesters, such as a large cutting resistance and poor cutting effect, combined with bionic engineering technology and biological characteristics, a bionic model was used to extract the characteristics of the cutting blades of locusta migratoria manilensis’s upper jaw. A 3D point cloud reconstruction and machine vision methods were used to fit the polynomial curve of the blade edge using Matlab 2016. A straw-cutting process was simulated using the discrete element method, and the cutting effect of the bionic blade was verified. Cutting experiments with rice straws were conducted using a physical property tester, and the cutting resistance of straw to bionic blades and general blades was compared. On the whole, the average cutting force of the bionic blades was lower than that of the general blades. The average cutting force of the bionic blade was 18.74~38.23% lower than that of a smooth blade and 1.63~25.23% lower than that of a serrated blade. Similarly, the maximum instantaneous cutting force of the bionic blade was reduced by 2.30~2.89% compared with the general blade, which had a significant drag reduction effect. By comparing the time–force curves of different blades’ cutting processes, it was determined that the drag-reducing effect of the bionic blade lies in shortening the straw rupture time. The larger the contact area between the blade and the straw, the more uniform the cutting morphology of the straw after cutting. Field experiment results indicate that the average power consumption of a straw chopper partially installed with bionic blades was 5.48% lower than one with smooth blades, measured using a wireless torque analysis module. In this research study, the structure of the straw chopper of an existing combine harvester was improved based on the bionic principle, which reduced resistance when cutting crop straw, thus reducing the power consumption required by the straw chopper and improving the effectiveness and stability of the blades.

Keywords: combine harvester; bionic blade; incisor lobe of locusta migratoria manilensis; rice straw; cutting experiment

1. Introduction

The annual output of agricultural straw in China is about 800 million tons, ranking first in the world since 2011. The improvement of the mechanization level in agricultural planting areas and the promotion of straw-mulching modes promote the demand for straw chopping and the dispersal of combine harvesters [1–4]. After threshing and separating crops using a combine harvester, impurities, such as branches, stalks and leaves, will be sent to a straw-cutting device and then distributed into the field. The straw chopper, in which blades are the main working components, is usually installed at the rear of the harvester [5]. The blades in a straw-cutting device are divided into fixed blades and rotating blades. When working, the rotating blades rotate at a high speed, and the fixed blades on the rack chop the straw into pieces through hitting and cutting. During this process, the blades are subjected to unstable and uneven resistance, so the blades need to operate at a
high cutting speed to cut the straw. Improving the cutting speed of the blade to achieve the effect of chopping the straw will result in additional power consumption. Taking the products of WORLD GROUP, which has the largest sales volume of crawler-type combine harvesters in China, as an example, the power of the whole machine is about 80 kW, and the average power consumption of the straw-cutting device is 8–10 kW, accounting for about 10–12.5% of the overall consumption of the whole machine. Therefore, developing blades with excellent cutting performance can effectively improve the cutting efficiency of the straw-chopping device and extend the service life of the blades, which is of great significance for reducing the overall power consumption of the harvester and improving the efficiency of returning straw to the field.

Existing studies show that based on the sliding cutting theory, a blade’s cutting resistance can be effectively reduced by changing the cutting mode, modifying the blade’s edge profile [6–9] or improving the overall structure of the blade [10]. Tian et al. [11] improved the design of the blade of a hemp-reaping machine based on the curve of longicorn teeth. Jia et al. [12] designed a bionic disc stubble cutter based on the curve of locust mouthparts. Jiang et al. [13] designed a blade for cutting corn stubble by referring to cricket mouthparts. Yang et al. [14] designed a bionic rotary blade based on the multi-toe combined structure and toe tip contour curve of a mole forelimb palm. Wang et al. [15] used the tibial curve of a mantis forelimb as a disc structure to cut the stems and leaves of carrots.

In the design process of various bionic blades, the DEM has been applied in blade simulations, parameter calibrations, and straw-crushing experiments with high reliability. Zhang et al. [16] used reverse-engineering technology to extract and fit the sliding cutting curve of the upper jaw of leaf-cutting ants and constructed a discrete element model of corn straw for simulated cutting experiments. Based on this, they completed the design of a crushing blade that mimics the upper jaw of leaf-cutting ants. These above research studies verified that these kinds of bionic agricultural blades, designed by referring to biological characteristics and conforming to actual working conditions, have excellent drag reduction and consumption reduction effects. However, straw-cutting device and blades have different ways of cutting straw. A combine harvester mainly cuts a large number of mixed and disorderly straw stems through a combination of rotating and fixed blades [17], while some cutting devices usually cut straw at the same position through reciprocating cutting or unsupported cutting [13,16]. At present, there is relatively little application of bionic blades in the straw-cutting devices of combine harvesters.

According to the above problems, this research takes locusta migratoria manilensis as a research object and proposes a kind of bionic locusta migratoria manilensis blade. Locusta migratoria manilensis is a common insect in various agricultural areas of China. This kind of insect mainly feeds on gramineous plants. During the adult stage, they have a huge appetite, and the time spent eating takes up about half of the whole life cycle. This kind of insect has highly developed chewing mouthparts in which the hard upper jaw is the main organ for chewing food and the incisor lobe at the front of the upper jaw is used to cut off food [18,19]. Based on the characteristics of locusta migratoria manilensis mouthparts, it can be used as a reference for the design and research of a cutting blade which needs to cut a large number and various kinds of crop straw. Therefore, an adult locusta migratoria manilensis was used as a bionic prototype; the overall size of the creature was measured, and consistency statistics were carried out. The partial contour curves of the left and right teeth were extracted as the blade curve, and imitation left and right teeth of locusta migratoria manilensis were designed. Through straw-cutting experiments, the changes in the cutting force of the bionic blade and a general blade were compared. Finally, the performance of the bionic blade was verified through field experiments. Based on the bionic principle, the structure of the blades on an existing harvester was improved to reduce resistance when cutting crop straw so as to reduce the power consumption of the straw-cutting device and improve the effect and stability of the blades.
2. Materials and Methods

2.1. Selection and Measurement of Biomimetic Prototypes

Zhao et al. [20] used the maxillary tooth blade of the cotton locust in corn harvester cutting blades. According to this method, research on locusta migratoria manilensis was carried out. The body of this kind of insect is usually smaller than cotton locust (as shown in Figure 1). Their living habits are also different from the cotton locust, belonging to the group of mass-migration organisms which can move and fly long distances. Their damage is even worse. In addition, locusta migratoria manilensis also have chewing mouthparts with excellent cutting performance. When feeding, they use the extension and contraction of the left and right incisors in the upper jaw to quickly cut plant tissues. The working process of a straw-cutting device is similar to the feeding process and feeding type of locusta migratoria manilensis. So, this research takes the teeth of locusta migratoria manilensis as its main research object.

![Figure 1. Locusta migratoria manilensis’s feeding process (female adult).](image)

The male adults of locusta migratoria manilensis have a body length of 33–48 mm, while female adults have a body length of 39–52 mm. The body size of female adults is generally larger than that of male adults, making them easier to measure. A batch of locusta migratoria manilensis female adults from a breeding farm in Bengbu, Anhui Province, were selected for observation. The overall dimensions of the same batch of female locusts were measured using a vernier caliper (DL92150P, Deli, Xiamen, China), as shown in Figure 2. The body length (from head to tail, excluding antennae), body width (on both sides of the abdomen and back) and body height (on both sides of the chest) of the female adults were as follows: 40.54 ± 2.61 mm, 8.30 ± 0.84 mm and 9.39 ± 0.50 mm.

![Figure 2. Overall measurement of Locusta migratoria manilensis dimensions.](image)

2.2. Reconstruction and Contour Extraction of Incisor Lobe

The size of the incisors on the upper jaw was measured using a super-depth 3D microscope (VHX-900F, Keenes, Japan). The length of the incisor blade was obtained using the image contactless measurement function of the instrument. As shown in Figure 3, the lengths of the left and right incisors of locusta migratoria manilensis were measured separately. Statistically, the size of the left incisor $l_1$ of a female locust was 2.36 ± 0.13 mm, and the size of the right incisor $l_2$ was 1.52 ± 0.14 mm. The contour curve of the right
incisor is raised and rounded, while that of the left incisor is gently concave. The length of the right incisor is similar to that of the left. When the two teeth are closed, the right incisor lobe will overlap in the depression of the left incisor lobe.

Figure 3. Measurements of incised teeth of locusta migratoria manilensis.

A bionic digital prototype was obtained based on the surface topography of the cutting teeth of the locust as a reference for the bionic blade’s design, and a reverse reconstruction of the cutting teeth was attempted. Since the cutting teeth of the locust are very small, it is difficult to generate position point cloud information on the surface topography of the teeth according to the accuracy of existing laser scanners. Therefore, image processing software (Agisoft PhotoScan2.0.1, Technology Co., LTD., Beijing, China) was used to reconstruct the teeth of the locust, as shown in Figure 4. Multiple consecutive images of the cutting teeth at different locations were collected. These 2D images were imported into image processing software and converted into 3D point cloud files for exportation. The 3D point cloud files were then imported into reverse-engineering software (Geomagic Studio 2012, Raindrop, Dallas, TX, USA) and CAD software (Solidworks 2020, Dassault Systemes, Waltham, MA, USA) to generate the required solid 3D model.

Figure 4. Reconstruction process of locusta migratoria manilensis cutting teeth.

The high-accuracy image of the incisor lobe contour obtained using the super-depth 3D microscope was imported into machine vision software (HALCON20.05, MVTEC, Bayern, Germany). A canny edge detection algorithm was used to extract the contour of the incisor lobe, and the coordinate information of the generated contour was exported in data format through a coordinate transformation. Specific steps are shown in Figure 5. Profile curves of the left and right incisors, as shown in Figure 6, were obtained. It can be seen that the profile features of the locust were irregular, but each curve of the cutting profile with different colors was convex in shape. The extracted contour curve was used as the edge shape of the bionic blades.

Figure 5. Specific flow chart of the extraction of the cutting blade’s contour.
The size information of the overall structure of the cutting teeth of locusta migratoria manilensis can be obtained through the physical mapping and 3D modeling of the measured data. We conducted preliminary surveying and modeling of the cutting teeth profile of locusta migratoria manilensis. Due to the complex surface of the cutting teeth, accurate position information cannot be obtained for non-edge dimensions. The error caused by manual measurement and mapping was significant, so the model differed greatly from the actual tooth structure. Considering the significant difference in the overall structure between the blades and the manilensis teeth, we extracted the contour curves of the cutting teeth for further research.

As shown in Figure 6, each curve of the cutting profile was segmented in which the right cutting profile was divided into 5 sections of a convex curve and the left cutting profile was divided into 6 sections of a convex curve. The curve-fitting tool in Matlab 2016 was used to fit each curve, and a curve-fitting equation for the left and right profiles with six terms was calculated (Equation (1)). The parameters of the constant terms are shown in Tables 1 and 2 by Equation (1), and the fitting degree $R^2$ values of the right and left cutting curve are no less than 0.9913 and 0.9324, showing good fitting performance. The coordinates of the fitting curve were intercepted with equal distance, and it was found that the fitting curve was basically consistent with the original curve, so the fitting cutting profile curve was used for the design of the cutting edges of the blades.

$$f(x) = p_1 \times x^6 + p_2 \times x^5 + p_3 \times x^4 + p_4 \times x^3 + p_5 \times x^2 + p_6 \times x + p_7$$

Table 1. Parameters of six-term fitting equation of left cutting tooth in Figure 6a.
Table 2. Parameters of six-term fitting equation of right cutting tooth in Figure 6b.

<table>
<thead>
<tr>
<th>Right Cutting Tooth (Color)</th>
<th>$p_1$</th>
<th>$p_2$</th>
<th>$p_3$</th>
<th>$p_4$</th>
<th>$p_5$</th>
<th>$p_6$</th>
<th>$p_7$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>curve1 (Black)</td>
<td>$4.46 \times 10^{-9}$</td>
<td>$-1.36 \times 10^{-6}$</td>
<td>$0.0001525$</td>
<td>$-0.007798$</td>
<td>$0.1569$</td>
<td>$1.459$</td>
<td>$0.4654$</td>
<td>$0.9999$</td>
</tr>
<tr>
<td>curve2 (Red)</td>
<td>$-2.20 \times 10^{-7}$</td>
<td>$1.10 \times 10^{-5}$</td>
<td>$-1.05 \times 10^{-5}$</td>
<td>$-0.007484$</td>
<td>$0.1038$</td>
<td>$0.213$</td>
<td>$79.3$</td>
<td>$0.9974$</td>
</tr>
<tr>
<td>curve3 (Blue)</td>
<td>$1.20 \times 10^{-7}$</td>
<td>$-2.14 \times 10^{-5}$</td>
<td>$0.001447$</td>
<td>$-0.04584$</td>
<td>$0.6451$</td>
<td>$-1.68$</td>
<td>$79.2$</td>
<td>$0.9913$</td>
</tr>
<tr>
<td>curve4 (Green)</td>
<td>$4.40 \times 10^{-9}$</td>
<td>$-1.75 \times 10^{-6}$</td>
<td>$0.0002267$</td>
<td>$-0.0119$</td>
<td>$0.2322$</td>
<td>$-0.781$</td>
<td>$84.7$</td>
<td>$0.9975$</td>
</tr>
<tr>
<td>curve5 (Purple)</td>
<td>$8.75 \times 10^{-10}$</td>
<td>$-3.15 \times 10^{-7}$</td>
<td>$4.31 \times 10^{-5}$</td>
<td>$-0.00281$</td>
<td>$0.0760$</td>
<td>$-0.0932$</td>
<td>$79.2$</td>
<td>$0.9989$</td>
</tr>
</tbody>
</table>

2.3. Design Modification of Bionic Blade Edge

The general cutting blades in the straw-cutting device of a combine harvester are straight types, mainly including smooth blades and serrated blades. Rotating blades and fixed blades can be used in pairs to improve the straw-cutting effect. The cutting edge is a straight, sharp and smooth blade or serrated blade. With reference to the blade used in the straw-cutting device, the extracted curve was used as the blade edge to design a bionic cutting blade based on locusta migratoria manilensis and to explore the cutting effect of this blade. A Ruilong 4LZ-6.0 crawler combine harvester was used as the object of this research. Smooth blades and serrated blades were used in the straw-cutting device of this harvester. On the basis of maintaining the same length, width, thickness and blade angle of the general blade, design modifications were carried out. As shown in Figure 7, under the condition that the overall dimension of the cutting blade was not changed, we selected the following sizes:

- $a$ is 50 mm,
- $b$ is 165 mm,
- $c$ is 3 mm,
- $h$ is 6.5 mm,
- $l$ is 86 mm and
- $k$ is 12.5 mm.

The contour of the locusta migratoria manilensis tooth was extracted as the blade shape, including the tooth interval $m$, tooth height $n$ and blade width $h$. Based on the blade length ($l$ = 86 mm) and the tooth height ($n$ = 1.5 mm), we decided on the following design sizes: the right tooth interval $m$ was 28 mm, the maximum tooth height was 3.39 mm, the left tooth interval $m$ was 34 mm and the maximum tooth height was 1.43 mm.

![Figure 7. Bionic cutting blades and general cutting blades. Note: I. the edge of the left tooth of the locusta migration manilensis blade; II. the edge of the right tooth of the locusta migration manilensis blade; III. a smooth-edge blade; IV. a serrated-edge blade. a means the blade width, mm; b means the blade length, mm; c means the blade thickness, mm; h means the blade width, mm; l means the blade length, mm; m means the tooth pitch, mm; n means the tooth height, mm; k means the diameter of the positioning hole, mm; $\alpha$ means the blade angle; A is an enlarged view of the serrated blade edge.](image)

Considering that the blade edge size may affect the cutting performance and effect, the original bionic cutting curve was proportionally adjusted. Several groups of bionic locust cutting contour curves with different cutting edge ratios were added in the modeling process. Two groups of curves at 75% and 50% of original size were added as the bionic right tooth contour curves (ratio of 0.75 and ratio of 0.5). A new set of curves at 75% of the
original size were added as the left tooth contour curves (ratio: 0.75). Since the maximum
tooth height of 50% of the original size of the left incisor profile curve was as small as
0.71 mm, the cutting edge was relatively smooth and similar to the light edge, so it was
not analyzed. Therefore, a total of 5 bionic blades with different cutting-edge types were
designed. Because the contours of the blade were a non-straight edge and a non-sharp
serrated edge, the unedged blade was processed by wire cutting. When the blade in the
straw-cutting device works, it needs to cut a large number of straw stems with random
movements and irregular sizes, and the blade is usually subjected to a large alternating
load. Thus, 65 Mn spring steel was chosen as the material, which has high strength and
wear resistance.

2.4. Discrete Element Simulation of Straw-Cutting Device’s Working Process

Due to the complex structure of the designed bionic blades and the high processing
cost, the cutting performance of the bionic blade was tested using the discrete element
method (DEM) before the blade was manufactured. The DEM is suitable for simulating
the cutting process of a large number of granular materials and evaluating whether the
cutting performance of the bionic blade in the straw-cutting device is better than that of the
general blade.

Before the cutting process begins, most of the materials entering a straw-cutting device
are long straw materials that are not screened by the concave plate in the front threshing
device. The length of most straw ranges from 100 to 500 mm. The main component of
straw is tough cellulose, so it is an orthogonal, anisotropic, flexible material. A flexible
model of rice straw was established, and a long rice straw stem was simplified into a hollow
cylinder with an outer diameter $d_2$ of 5 mm, a wall thickness $d$ of 0.5 mm and a length of
150 mm without considering the internode structure of the straw, as shown in Figure 8.
The size distribution operation command in EDEM software was used to limit the length
of long rice straw stems to 100-500mm. In order to characterize the breaking of the straw
in the simulation, it is necessary to bond the particles of the straw. The Hertz–Mindlin
contact model with bonding (as shown in Table 3) was built using discrete element software
(EDEM 2022, Altair Engineering Inc., Troy, MI, USA). Particle viscosity can be expressed by
the bonding between particles, which can well replace the fibers’ connections in the straw.
Relevant research studies and applications have been carried out by scholars [21,22].

![Figure 8. Particle model of rice straw ($l_2 = 150$ mm, $d_2 = 5$ mm, $d = 0.5$ mm).](image)

<table>
<thead>
<tr>
<th>Bonding Radius (mm)</th>
<th>Normal Bond Stiffness ($N/m^3$)</th>
<th>Tangential Bond Stiffness ($N/m^3$)</th>
<th>Normal Critical Stress (Pa)</th>
<th>Tangential Critical Stress (Pa)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.55</td>
<td>$1.5 \times 10^{10}$</td>
<td>$1 \times 10^{10}$</td>
<td>$5 \times 10^8$</td>
<td>$5 \times 10^8$</td>
<td>[12,21]</td>
</tr>
</tbody>
</table>

The straw-cutting device of the combine harvester included an outer shell, roller,
rotating blade rack, rotating blade and fixed blade. In order to reduce the simulation’s
calculation time, the model of the straw chopper was simplified by removing unnecessary
parts from the model, reserving only the outer shell, rotating blade, fixed blade and roller.
The roller was connected to the blade rack, and a guiding plate was added at the inlet of
the straw-cutting device. The simplified model is shown in Figure 9. The blue arrow in the
figure represents the direction of straw feeding, and $v$ refers to the initial speed. The red
arrow represents the direction of roller rotation, and $w$ refers to the angular velocity.
After establishing the simplified model of the straw-cutting device and the model of straw, the motion characteristics of the device were defined, and the particle factory was set up. The rotating speed of the device is usually 2500–3500 r/min, so the roller rotating speed was set as 3000 r/min, and the material of the simplified model was set as steel. During the simulation process, the number of straw stems was 30 per second, and the model of the stem particles was generated using particle replacement. The particle generation time was 0.01 s, the bond generation time was 0.011 s, and the simulation time was 1.5 s. An initial velocity of 5 m/s was applied along the horizontal positive $\times$ direction to the entrance of the guiding plate, and the gravitational acceleration was $9.81 \text{ m/s}^2$. The simulation model is shown in Figure 10. The blades in the straw-cutting device were replaced with bionic blades (at a ratio of 1). The cutting performances of the bionic blade and the smooth blade were compared through this simulation, that is, the left bionic locust blade locust was used as the fixed blade, and the right bionic blade was used as the rotating blade. According to related studies by scholars on the material parameter characteristics and interaction characteristics of rice straw, the material properties and parameters of rice straw required by the discrete element simulation [23,24] were set as shown in Tables 3–5.

**Table 4. Material parameters.**

<table>
<thead>
<tr>
<th>Simulation Material</th>
<th>Poisson’s Ratio</th>
<th>Shear Modulus (MPa)</th>
<th>Density (kg/m$^3$)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rice stem</td>
<td>0.4</td>
<td>1</td>
<td>215</td>
<td></td>
</tr>
<tr>
<td>Steel</td>
<td>0.3</td>
<td>206,000</td>
<td>7800</td>
<td>[23,24]</td>
</tr>
</tbody>
</table>

**Figure 9.** Simplified straw-cutting device.

**Figure 10.** Process of cutting rice straw (a. bionic blade; b. smooth blade).
### Table 5. Contact parameters between materials.

<table>
<thead>
<tr>
<th>Contact Parameter</th>
<th>Restitution Coefficient</th>
<th>Static friction Coefficient</th>
<th>Rolling Friction Coefficient</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rice stem—rice stem</td>
<td>0.2</td>
<td>0.9</td>
<td>0.01</td>
<td>[23,24]</td>
</tr>
<tr>
<td>Rice stem—steel</td>
<td>0.2</td>
<td>0.8</td>
<td>0.01</td>
<td></td>
</tr>
</tbody>
</table>

#### 2.5. Process and Result Analysis of Discrete Element Simulation

As shown in Figure 11, the rice straw enters the guiding plate and breaks after hitting the sharp edge of the blade. In the post-processing stage of the simulation, information about the force change of the blade cutting straw with time can be obtained, and the process of cutting rice straw entering the cutting device with different kinds of rotating and fixed blades was analyzed.

![Figure 11. Process of chopping rice straw.](image)

As shown in Figure 12, the force of cutting rice straw using the bionic blade was generally less than that of the smooth blade in the cutting process. Each peak point is the cutting force received by the straw when the blade contacted the straw. The cutting forces at each peak point were counted to obtain the average peak cutting force received by straw. The average peak cutting force received by the rice straw from the bionic blade group was 4.17 N, and that from the smooth blade group was 7.57 N, which was reduced by approximately 44.9%. The simulation results show that the bionic blade can effectively reduce the cutting force received by rice straw when compared with a general smooth blade.

![Figure 12. Force of cutting rice straw using a bionic blade and a smooth blade.](image)

In the simulation process, the cutting force of the bionic blade was less than that of the smooth blade, which was closely related to the blade shape. Figure 13 shows the contact force between straw stalks of several different cross-section sizes and the bionic blade. Compared with the single-point contact of the smooth blade when cutting the straw, the straw contacts multiple raised ridges on the bionic blades and thus provides force to the straw surface in multiple places. Under the same conditions, the degree of deformation...
caused by multi-point contact cutting with a bionic blade was more significant than that caused by single-point contact cutting with a smooth blade.

Figure 13. Contact condition of straw when being cut by bionic and smooth blades.

2.6. Cutting Experiment Using Rice Straw

Through the simulation experiment, the cutting effect of the bionic blade was initially verified to be obvious, so the trial production of a bionic blade was carried out for the rice straw cutting experiment. The cutting effects of the bionic blade and the general blade were compared according to the cutting force value received by the straw.

2.6.1. Materials and Equipment

The types of cutting blades were a left/right tooth bionic blade and a general smooth/serrated blade, as shown in Figure 14. The rice straw samples were collected from a rice field to be harvested in World farmland, Zhenjiang City, Jiangsu Province, as shown in Figure 15. The rice variety was Zhen’nuo 762. It was measured that the average height of the rice straw plants here was 903 mm, and the rice straw had a height of 120 mm above the ground. The average outer diameter of the straw at the cutting point was 7.97 mm. The straw stems of rice are upright tillers branching from the main stems with small angles. Therefore, rice straw stems with a cross-sectional diameter of about 5 mm and a deviation of less than 0.5 mm were selected as test samples.

Figure 14. Cutting blades with different curves used in the experiment. Note: (a) is the right tooth bionic blade, ratio: 1, 0.75, 0.5; (b) is the left tooth bionic blade, ratio: 1, 0.75; (c) is the general smooth blade; (d) is the general serrated blade.
In order to explore the difference in cutting straw with the left (right) blade and the general (smooth, serrated) blade, we compared the cutting effects of different blade types. We also took rice straw stems as cutting samples and measured the force required to cut the straw via mechanical testing equipment. As shown in Figure 16, the rice straw cutting test was conducted using a physical property tester (TA. XT PLUS100C, SMS Company, London, UK) which measured the force range of 0–5 kN. At a loading speed of 0.1–10 mm/s, the force sensor’s accuracy was 0.025%. A self-made straw-clamping device was used to fix the testing sample and adjust the support distance at both ends of the sample. The self-made clamping device was connected to the physical property tester to fix the blade position and adjust the sliding cutting angle, as shown in the enlarged image of the left part pointed by the arrow in Figure 16. When the physical property tester was loaded at a constant speed controlled by the computer, the blade moved toward the loading table. Once it touched the straw, the physical property tester was triggered to record the force, displacement and time until the sample was completely cut off.

Figure 15. Rice straw for the cutting test.

Figure 16. Cutting force test using rice straw (1. physical property tester; 2. self-made stem-clamping device; 3. blade; 4. self-made tool-clamping device).

2.6.2. Test Method

The main factors affecting the cutting force of the straw included the loading speed of the texture instrument, the cutting angle of the blade and the supporting distance between the two ends of the straw [25,26]. In order to ensure the measuring accuracy of the texture instrument, the maximum loading speed was set to 10 mm/s. According to the principle of slip cutting, the smaller the cutting edge angle, the more labor-saving the cutting is. Considering the range of cutting angles selected in previous related research studies [27,28], the cutting angle was always set from 20° to 30°. The average cutting force in the experimental data is given by the time–force curve of the analyzer, and the average
cutting force and maximum instantaneous cutting force were recorded for subsequent analysis. The equation for the average cutting force is

\[ F = \frac{1}{n} \sum_{i=1}^{n} F_i \]  

(2)

In Equation (2), \( F \) is the mean cutting force, \( N \); \( F_i \) is the force measured per sample, \( N \); and \( n \) is the total number of sampling points of the texture instrument when cutting the stem. Each group of experiments was repeated three times to measure the maximum and average values of cutting resistance, as shown in Figure 17.

Figure 17. The display interface of physical tester.

3. Results and Analysis

3.1. The Influence of Different Factors on the Straw-Cutting Force

To determine appropriate experimental parameters, orthogonal experiments were conducted with a general smooth blade as the main research object. The main experimental factors affecting the straw-cutting force included the loading speed of the texture analyzer, the cutting angle of the blade and the support distance at both ends of the straw. To ensure the measurement accuracy of the texture analyzer at 0.025%, the maximum loading speed was set to 10 mm/s. The magnitude of the cutting force is related to the angle at which the blade cuts the straw, and the cutting angle is relatively easy to cut within a certain range generally not exceeding 60°. The size of the straw support distance also has an impact on the cutting force. Cutting with support is more labor-saving than cutting without support. It was measured that the distance between the fixed blades of the straw-cutting device of the World machine was 30 mm, so it was used as the intermediate horizontal value of the experimental factor. Based on the cutting angle values and ranges selected in the reference literature for rice-straw-cutting experiments [27,28], cutting angles of 20°, 25° and 30° were selected. The texture analyzer drives the smooth blade to apply a load to cut the straw at loading speeds of 4 mm/s, 7 mm/s and 10 mm/s. The straw support distances were 20 mm, 30 mm and 40 mm, as shown in Table 6. The average cutting force in the experimental data is given by the time–force curve of the texture analyzer, and only the average cutting force is used as an indicator. The results of the maximum instantaneous cutting force recorded in the experiment are not significant, so the maximum instantaneous cutting force will not be analyzed here.

Table 6. Test-related factors and level table.

<table>
<thead>
<tr>
<th>Level</th>
<th>Cutting Angle A (°)</th>
<th>Loading Speed B (mm/s)</th>
<th>Supporting Distance C (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20</td>
<td>4</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>25</td>
<td>7</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>30</td>
<td>10</td>
<td>40</td>
</tr>
</tbody>
</table>
As shown in Table 7, during the experiment, under the conditions of a blade cutting angle of 30°, a loading speed of 10 mm/s and a support distance of 30 mm between the straw stems at both ends, the average cutting force received by a single rice straw stem was the smallest, which was 14.86 N. Under the conditions of a blade cutting angle of 20°, a loading speed of 7 mm/s and a support distance of 30 mm between the straw stems at both ends, the maximum average cutting force received by a single rice straw stem was 18.37 N. The range analysis results indicate that the degree of influence of each factor on the average cutting force on the straw is in the descending order of loading speed, cutting angle and support distance. The optimal experimental parameters are as follows: a loading speed of 10 mm/s, a cutting angle of 30° and a support distance of 40 mm.

Table 7. L_9(3^4) orthogonal test results and range analysis.

<table>
<thead>
<tr>
<th>Test Serial Number</th>
<th>Cutting Angle A(°)</th>
<th>Loading Speed B (mm/s)</th>
<th>Supporting Distance C (mm)</th>
<th>Error Column D</th>
<th>Average Cutting Force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20</td>
<td>4</td>
<td>20</td>
<td>1</td>
<td>17.6963</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>7</td>
<td>30</td>
<td>2</td>
<td>18.3657</td>
</tr>
<tr>
<td>3</td>
<td>20</td>
<td>10</td>
<td>40</td>
<td>3</td>
<td>15.4077</td>
</tr>
<tr>
<td>4</td>
<td>25</td>
<td>4</td>
<td>30</td>
<td>3</td>
<td>17.0060</td>
</tr>
<tr>
<td>5</td>
<td>25</td>
<td>7</td>
<td>40</td>
<td>1</td>
<td>16.9963</td>
</tr>
<tr>
<td>6</td>
<td>25</td>
<td>10</td>
<td>20</td>
<td>2</td>
<td>15.0533</td>
</tr>
<tr>
<td>7</td>
<td>30</td>
<td>4</td>
<td>40</td>
<td>2</td>
<td>15.0500</td>
</tr>
<tr>
<td>8</td>
<td>30</td>
<td>7</td>
<td>20</td>
<td>3</td>
<td>17.9763</td>
</tr>
<tr>
<td>9</td>
<td>30</td>
<td>10</td>
<td>30</td>
<td>1</td>
<td>14.8603</td>
</tr>
</tbody>
</table>

k_1 17.1566 16.5858 16.9088 16.5177
k_2 16.3519 17.7796 16.7440 16.1580
k_3 15.9640 15.1071 15.8197 16.7968

Range value 1.1925 2.6725 1.0891 0.6388
Optimal level A_3 B_3 C_3
Optimal combination B_3 A_3 C_3

The results of an analysis of variance are shown in Table 8. In the orthogonal experiment, there was no significant difference (p > 0.05) in the average cutting force for the experimental factors such as the cutting angle, loading speed and support distance, indicating that the average cutting force of the smooth blade for a single rice straw stem was not significantly affected by these three levels of factors.

Table 8. Analysis of variance for orthogonal test results.

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares</th>
<th>Freedom</th>
<th>Mean Square</th>
<th>F</th>
<th>p-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.7400</td>
<td>2</td>
<td>0.3700</td>
<td>3.6078</td>
<td>0.2170</td>
</tr>
<tr>
<td>B</td>
<td>3.5846</td>
<td>2</td>
<td>1.7923</td>
<td>17.4797</td>
<td>0.0541</td>
</tr>
<tr>
<td>C</td>
<td>0.6893</td>
<td>2</td>
<td>0.3446</td>
<td>3.3603</td>
<td>0.2293</td>
</tr>
<tr>
<td>Error</td>
<td>0.2051</td>
<td>2</td>
<td>0.1026</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>5.2190</td>
<td>8</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

According to Figure 18, the results indicate that within the experimental level, the influence of loading speed on the average cutting force fluctuates significantly. As the loading speed increases, the average cutting force first increases and then decreases, and the cutting angle and support distance are negatively correlated with the average cutting force; the smaller the force used to cut the stem, the better the cutting effect of the blade.
3.2. Cutting Experiment with Different Blade Cutting Edges

Cutting tests were carried out using different blade cutting edges with a loading speed of 10 mm/s, a cutting angle of 30° and a support distance of 40 mm, according to the results of the orthogonal experiments. As shown in Figure 19, the mean cutting force of the right bionic blade (ratio 0.75) on the straw was the smallest, while that of the smooth blade was the largest. The instantaneous cutting force measured from the serrated blade was the largest, while the right bionic blade’s instantaneous cutting force (ratio 0.75) was the smallest. On the whole, the average cutting force of the bionic blade is 18.74–38.23% lower than that of smooth blade and 1.63–25.23% lower than that of the serrated blade. Similarly, the maximum instantaneous cutting force of the bionic blade was lower than that of the general blade. The smaller the peak force of the blade is, the smaller the impact degree of the blade is. The maximum instantaneous cutting force of the bionic blade was 2.30–2.89% lower than that of the general blade. The maximum instantaneous cutting forces of different blades were about double the value of the average cutting force. As shown in Table 9, the average cutting force of blades with different blade types at the confidence level of 0.05 in the test was 0.027 ($p < 0.05$), and blades with different blade types had a significant impact on the overall cutting effect. The $p$-value of the maximum instantaneous cutting force was 0.789 ($p > 0.05$), and the difference between blades with different blade types was not significant at the confidence level of 0.05.
Table 9. ANOVA results of a single-factor test of rice straw ($\alpha = 0.05$).

<table>
<thead>
<tr>
<th>Source of Differences</th>
<th>The Average Cutting Force/N</th>
<th>The Maximum Instantaneous Cutting Force/N</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Interblock Parameters</td>
<td>Interclass Parameters</td>
</tr>
<tr>
<td>SS</td>
<td>43.740</td>
<td>29.864</td>
</tr>
<tr>
<td>df</td>
<td>6</td>
<td>14</td>
</tr>
<tr>
<td>MS</td>
<td>7.290</td>
<td>2.133</td>
</tr>
<tr>
<td>F</td>
<td>3.418</td>
<td>0.513</td>
</tr>
<tr>
<td>p-Value</td>
<td>0.027</td>
<td>0.789</td>
</tr>
<tr>
<td>F crit</td>
<td>2.848</td>
<td></td>
</tr>
</tbody>
</table>

Note: SS means the sum of squares, df means the degree of freedom, MS means the mean square, F means the test statistic, p-value means the observed significance level, and F-crit means the test threshold. The same is true below.

3.3. Straw Cutting Experiment Using Combined Blades

In the single-factor rice-straw-cutting test, the average cutting force of the right bionic blade (ratio of 0.5) was larger, so the bionic blade was ignored in the combination experiment to simplify the number of experimental groups. Only the entire combination experiment of the four blade types of the left bionic blade (ratios of 0.75 and 1) and right bionic blade (ratios of 0.75 and 1) was carried out. As shown in Figure 20, the test conditions were the same as in the single-factor test, and each test was repeated three times, with a total of 48 groups. The average cutting force was taken as the test index. As shown in Table 10, three groups of rotating–fixed blade combination blades with the minimum average cutting force were selected. The combination modes of the rotating–fixed blade were $R^1 - R^1$, $R^{0.75} - R^1$ and $R^1 - R^{0.75}$ in ascending order. As shown in Figure 21, there was little difference in the size of the rice straw in the experiment; therefore, the scatter distributions of the right bionic serrated rotating–fixed blade combination (red rectangle) and the left bionic rotating–fixed blade combination (blue prismatic point) were observed. Overall, the cutting effect of the right bionic blade is better than that of the left bionic blade.

Figure 20. Combined cutting test of bionic blades.

Table 10. The result of the test of combined bionic blades.

<table>
<thead>
<tr>
<th>(The Average Cutting Force/N)</th>
<th>Types of Fixed Blade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Types of Rotating Blade</td>
<td>$R^1$</td>
</tr>
<tr>
<td>$R^1$</td>
<td>7.110</td>
</tr>
<tr>
<td>$R^{0.75}$</td>
<td>9.583</td>
</tr>
<tr>
<td>$L^1$</td>
<td>11.750</td>
</tr>
<tr>
<td>$L^{0.75}$</td>
<td>11.519</td>
</tr>
</tbody>
</table>

Note: $R^1$ and $R^{0.75}$ means right-tooth bionic blade; $L^1$ and $L^{0.75}$ means left-tooth bionic blade.
3.4. Load-Time Process Analysis of Cutting Processes with Different Blades

The force–time curves of cutting straw with different blades are shown in Figure 22, which can be divided into different cutting stages according to the time when the cutting force suddenly drops in a short time.

In the initial cutting stage of the smooth blade, the straw was compressed and deformed by the blade, but the outer epidermal tissue of the straw was not damaged, and the linear increase in the ultimate stress resistance of the straw was proportional. In the second cutting stage (II), the cutting force drops almost instantly after the straw epidermis breaks, and the inner wall of the other end of the straw begins to be cut under pressure. At this point, the cutting process starts from the inner wall of the straw to the outer epidermal tissue. The blade cuts directly with the wood fiber in the straw, and there is a cutting compression stage with a fluctuation and increase. This process was similar to the first cutting stage (I) and showed a linear upward trend until the straw compression force reached the limit again. In the third cutting stage (III), the cutting force gradually decreased after maintaining a stable cutting state for a period of time as the epidermal area of the remaining straw to be cut gradually decreased. In addition, the cutting force will rise sharply at this stage, and the straw is not in the cutting process but in the gliding fracture process.

In the initial cutting stage of the serrated blade, damage from a partial tooth tip on the outer wall of the straw can be obviously observed. With the increasing pressure of the blade on the straw during cutting, the straw fiber is cut off by constant friction from
the tooth tip, and the cutting force decreases to a certain extent at the moment when the straw is partially cut off. With increasing in the contact surface between the blade and the straw, the cutting force still fluctuates before reaching the ultimate pressure resistance of the stem. After reaching the maximum instantaneous cutting force, the cutting force enters the second cutting stage (II), and the cutting force drops sharply. Generally speaking, the serrated blade has a distinct two-stage cutting process, with the maximum instantaneous cutting force as the dividing line.

The cutting process of the left bionic locust blade is similar to that of the smooth blade. In the initial cutting stage (I), the force required to break the outer wall of the straw is relatively small due to the multi-point contact between the blade and the stem. In the second cutting stage (II), with the increase in the contact area, the cutting force showed a trend of continuous fluctuation before reaching the ultimate resistance. In the third cutting stage (III), before the end of the cutting stage, there was a small tension fracture in the straw, and the overall decreasing trend of the cutting force was relatively stable.

In the initial stage of cutting (I), the tip part of the right bionic locusta migratoria manilensis blade first contacted the stem, resulting in a small compressive area on the straw and a large local stress. Therefore, the outer wall of the straw was deformed and damaged under a small amount of pressure within a short time, resulting in a small cutting peak force. In the second cutting stage (II), the straw was cut by the edge at both ends of the tooth tip, which is similar to the second cutting stage of the smooth blade. When the compression limit of the straw is reached (III), the cutting force drops suddenly. After a period of stable linear decline, the straw is completely cut off.

### 3.5. The Influence of Blade Parameters on the Cutting Effect

Figure 23 shows incisions in straw stems cut by blades with different cutting edges. The incisions in straw stems cut by blades with different cutting edges were not neat, and there were obvious longitudinal tearing marks. The incisions in straws stems cut by blades with serrated edges were neat, but there were obvious longitudinal cracks. The incisions in straw stems cut by left bionic blades have no obvious longitudinal cracks. In the case of the right bionic blade, the cutting incision in the straw was neat, and there was no visible longitudinal crack. The degree of compression resistance to the deformation of the straw stem during cutting was relatively light, and it would not produce obvious compression deformation like the smooth blade, nor would the serrated blade frequently pull the longitudinal fiber of the straw.

![Figure 23. Incisions in straw stems after cutting using different types of blades.](image)

According to Figure 23 and Table 11, the changing trend in the cutting force over time was related to the design parameters of the blade cutting edge, and the tooth height reflected the smoothness of the blade curve to some extent: the larger the relative tooth height of the blade cutting edge was, the smaller the curvature of the blade cutting edge curve was, and the sharper the blade cutting edge was and the easier it was to destroy
the tough epidermis of the straw, especially hollow, thin-walled straw like rice. The tooth interval had a certain relationship with the cutting gap between the straw and the blade.

### Table 11. Dimensional parameters of straw chopper affecting cutting force.

<table>
<thead>
<tr>
<th>Design Parameters of Blade</th>
<th>The Maximum Tooth Height/mm</th>
<th>The Maximum Tooth Interval/mm</th>
<th>The Minimum Tooth Interval/mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>smooth blade</td>
<td>0</td>
<td>1.9</td>
<td>1.9</td>
</tr>
<tr>
<td>serrated blade</td>
<td>1.5</td>
<td>1.9</td>
<td>1.9</td>
</tr>
<tr>
<td>Right-tooth bionic blade (ratio 1)</td>
<td>3.39</td>
<td>8</td>
<td>3.5</td>
</tr>
<tr>
<td>Right-tooth bionic blade (ratio 0.75)</td>
<td>2.54</td>
<td>6</td>
<td>2.625</td>
</tr>
<tr>
<td>Right-tooth bionic blade (ratio 0.5)</td>
<td>1.70</td>
<td>4</td>
<td>1.75</td>
</tr>
<tr>
<td>Left-tooth of bionic blade (ratio 1)</td>
<td>1.43</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>Left-tooth of bionic blade (ratio 0.75)</td>
<td>1.07</td>
<td>4.5</td>
<td>0.75</td>
</tr>
</tbody>
</table>

The large tooth interval relative to the straw diameter meant that there was a large cutting gap which increased the cutting area between the blade and the straw. When the size of the straw section was not different from the size of the tooth interval, the straw could be cut in the cutting gap. Slippage between the straw and blade was reduced, which was beneficial to straw cutting and improving cutting quality.

In the process of conducting the rotating blade and fixed blade combination test, as the rotating blade was loaded at a low speed, the two ends of the straw stem would slip and were not easily cut by the rotating blade without being fixed, and the cutting force measured by the texture instrument would be smaller than the actual one. When the fixed blade supported both ends of the straw, the straw was rubbed and split at the fixed blade cutting edge after being squeezed, as shown in Figure 24. When the blade cut the straw with a different cutting edge, the slippage degree of the straw at the fixed edge was different. The cutting edge of the right-tooth bionic locusta migratoria manilensis blade cut the straw epidermis more easily at the supporting point than the left one, mainly because the curvature of the right blade’s cutting edge was smaller than that of the left one and the tooth height was larger, preventing the straw from sliding along the fixed blade. The cutting gap of the right cutting edge was larger than that of the left one, which increased the contact length between the blade and the straw per unit length and increased the stress area of the straw. Therefore, the right-tooth bionic blade needs less energy than the left-tooth bionic blade.

![Figure 24. Slip splitting while cutting rice straw.](image)
4. Field Experiment
4.1. Field Experiment Scheme

In order to further research the drag reduction effect of the bionic blade under actual working conditions, the power consumption of the straw-cutting device was detected by the torque sensor, and the power consumption of the straw-cutting device was compared with that of the smooth blade and the bionic blade installed successively. Power was measured by the non-contact method. Strain gauges were pasted on the rotating roller, wireless torque module and power supply module. A wireless module received the signals and transmitted them to a computer [29]. A DH5905 (Donghua Testing Co., Ltd., Jiangsu, China) wireless torque test and analysis module and power module were selected for the torque sensor. A BF350-6EA special torque strain gauge was selected in which the strain gauge resistance value was $350.0 \pm 1.5 \Omega$ and the sensitivity coefficient was $2.08 \pm 1\%$. The installation positions of the strain gauge and sensor are shown in Figure 25.

The test site was a rice experimental field in World farmland, Zhenjiang City, Jiangsu Province, and the rice variety was Zhen’nuo 762. A torque strain gauge was installed on the roller, and a wireless analysis module and power supply module were symmetrically arranged on the roller. Due to the high speed of the cutting device (usually between 2000 RPM and 4000 RPM), the modules were fixed with self-made sensor brackets. The sensor brackets are wrapped with tape and secured with ties to protect the sensors and transmission wiring harnesses. In the installation of bionic blades, considering the time and cost, only four right bionic blades were replaced as a group of rotating blades and four left bionic blades were replaced as fixed blades for cutting. The on-site installation and layout are shown in Figure 26. The plot size of the test site was 2 m $\times$ 20 m, and each harvesting distance was 20 m, which was divided into three groups: the starting distance was 5m, the monitoring distance was 10m and the end distance was 5m. Each section was marked with a flag. The torque calculation function of the Donghua testing software can obtain the corresponding torque value from a measured strain value. According to the outer diameter (114 mm), wall thickness (10 mm) and material (16 Mn) of the roller of the straw chopper, the test of the shaft power during the operation of the straw-cutting device could be realized using the calculation equation [30] of torque and power. The sampling frequency was 500 Hz. The torque and power of the bionic blade and the smooth blade during no-load rotation and the working process were measured, respectively.
4.2. Field Experiment Results

From startup to idling, the belt wheel of the combine harvester was attached with a reflective strip on the rotating roller of the straw-cutting device, and the rotational speed of the roller was measured to be 3165.96 r/min using a hand-held tachometer. According to the torque calculation function of the Donghua testing software, the measured torque of the straw-cutting device during no-load rotation was 10.43 N·m. The average power was 3.27 kW. As shown in Table 12, when the forward speed was 0.5 m/s during full-width cutting, the measured torque of the straw-cutting device with bionic blades was 32.711 N·m. Under the condition of a constant rotation speed of 3000 r/min, the average power consumption of the straw-cutting device with bionic blades was 9.713 kW during full-width cutting, which was 5.48% lower than that of the straw-cutting device with all smooth blades. A variance analysis was performed on the measured power consumption data, as shown in Table 13. The calculated $p$-value is 0.0324, which is less than 0.05. The bionic blade has a significant effect on reducing the power consumption of the straw-cutting device. The results of the field experiments to some extent indicate that using bionic blades as a new type of straw-cutting blade is feasible for reducing the cutting resistance of rice straw stems and the cutting power consumption of the cutting device.

Table 12. Torque and power consumption results in field trials.

<table>
<thead>
<tr>
<th>Number</th>
<th>General Cutting Blades</th>
<th>Bionic Cutting Blades</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Measured Torque (N·m)</td>
<td>Average Power (kW)</td>
</tr>
<tr>
<td>1</td>
<td>30.6765</td>
<td>9.637</td>
</tr>
<tr>
<td>2</td>
<td>31.02175</td>
<td>9.745</td>
</tr>
<tr>
<td>3</td>
<td>31.7225</td>
<td>9.965</td>
</tr>
<tr>
<td>4</td>
<td>34.33625</td>
<td>10.786</td>
</tr>
<tr>
<td>5</td>
<td>34.15675</td>
<td>10.730</td>
</tr>
<tr>
<td>6</td>
<td>33.3745</td>
<td>10.484</td>
</tr>
<tr>
<td>7</td>
<td>33.75325</td>
<td>10.603</td>
</tr>
<tr>
<td>8</td>
<td>32.64325</td>
<td>10.254</td>
</tr>
<tr>
<td>Average value</td>
<td>32.711 ± 1.426</td>
<td>10.276 ± 0.448</td>
</tr>
</tbody>
</table>
Table 13. Variance analysis of the average power consumption of smooth and bionic blades.

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares</th>
<th>Freedom</th>
<th>Mean Square</th>
<th>F</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inter group</td>
<td>1.26664</td>
<td>1</td>
<td>1.26664</td>
<td>4.60011</td>
<td>0.03239</td>
</tr>
<tr>
<td>Intragroup</td>
<td>3.14403</td>
<td>14</td>
<td>0.22457</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>4.41067</td>
<td>15</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5. Conclusions

Based on the design parameters of the existing blade and the extracted bionic contour curve, different blade types (contour ratios of 1, 0.75 and 0.5) were designed to simulate locusta migratoria manilensis teeth. The main conclusions were as follows:

1. In this research study, a physical property tester was used to test the cutting force of cutting a single rice straw stem. Compared with general smooth blades and serrated blades, the average cutting force of bionic blades was 18.74–38.23% lower than that of smooth blades and 1.63–25.23% lower than that of serrated blades. The maximum instantaneous cutting force of the bionic blades is 2.30–2.89% lower than that of the general blades. Compared with the left bionic blade, the right bionic blade has a better cutting effect when combined with a fixed blade, and the minimum average cutting force is obtained when the contour ratio is 1.

2. The cutting processes of different blade types are different. In the initial cutting stage, the tooth tip of the bionic blade can cut into the epidermis of the straw with a large cutting force and then slide to cut the edge of the epidermis of the straw from the inclined plane on both sides at the same time, increasing the contact area with the straw, reducing the cutting force correspondingly and saving the energy for cutting. Compared with the cutting morphologies of different blade types, the cutting smoothness of the bionic blade is better, and the degree of compression deformation is relatively low.

3. Field experiments show that the power consumption of the straw-cutting device with a quarter of bionic blades installed is 5.48% lower than that of a device with smooth blades installed under actual working conditions, which further verifies that the bionic blade has a certain drag reduction effect.

Author Contributions: Conceptualization, J.H., L.X. and Y.Y.; data curation, J.H. and J.L.; formal analysis, J.H. and X.C.; funding acquisition, L.X.; investigation, Q.W.; methodology, D.H.; project administration, J.H.; resources, L.Z.; software, Y.Y.; supervision, J.H. and X.C.; writing—original draft, J.H.; writing—review and editing, L.X. and Y.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Jiangsu Province and Education Ministry Co-Sponsored Synergistic Innovation Center of Modern Agricultural Equipment (XTCX1009), a Jiangsu Province Agricultural Science and Technology Independent Innovation Funds Class II Project (CX (21) 2042), the Priority Academic Program Development of Jiangsu Higher Education Institutions (No. PAPD-2018-87), and the Shandong Province Key R&D Program (Science and Technology Demonstration Project) Project (2022SFGC0201).

Institutional Review Board Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: Author Linjun Zhu was employed by the company Jiangsu World Agricultural Machinery. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.
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