

Article

Experimental Study on the Design and Cutting Mechanical Properties of Bionic Pruning Blades

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Abstract: This study focuses on existing pruning equipment; cutting blades show cutting resistance and lead to high energy consumption. Using finite element (FEA) numerical simulation technology, the branch stress wave propagation mechanism during pruning was studied. The cutting performance of the bionic blade was evaluated with cutting energy consumption as the test index and the branch diameter and branch angle as the test factors, respectively. The test results showed that the blades imitating the mouthparts of the three-pecten bull and the beak of the woodpecker performed well in pruning, and the energy consumption during cutting was reduced by 18.2% and 16.3% compared to traditional blades, making these blades significantly better. These two blades also effectively reduced the cutting resistance and branch splitting by optimizing the edge angle design and increasing the slip-cutting action. In contrast, the imitation shark's tooth blade increased cutting energy consumption by 14.4% due to the large amount of cutting resistance in the cutting process when cutting larger-diameter branches, making it unsuitable for application in the pruning field. Therefore, the blades imitating the mouthparts of the three pectens and the beak of the woodpecker have significant advantages in reducing the cutting resistance and improving the pruning quality. These findings provide an important theoretical reference for the development of energy-efficient pruning equipment.

Keywords: pruning; stopping; bionics; finite elements; cutting mechanism; cutting energy consumption



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1. Introduction

In agroforestry, branch pruning is a common nurturing technique aimed at promoting tree growth, adjusting morphological structure, and improving yield and quality. This technology is widely used, covering a wide range of agroforestry crops and tree species such as fruit trees and forest trees. At present, the pruning methodology is transitioning from manual techniques to mechanized approaches. Among these approaches, impact pruning equipment is distinguished by its remarkable adaptability and high efficiency. Noteworthy examples include the Chinese Monkeybot robot [1] and the German Patas robot [2]. However, the existing irrational pruning methods are one of the main factors leading to high production costs. Therefore, it is of great significance to explore the branch pruning mechanism, reduce the energy consumption of pruning operations, and optimize the pruning strategy through research on and the development of energy-efficient products.

At present, scholars have carried out a great deal of research work focusing on equipment that can cut the branches and stalks of agricultural and forestry crops. This is mainly reflected in the studies on blade cutting parameters, which include the blade wedge angle [3], blade slip angle [4], cutting speed [5], etc. Meng et al. used numerical simulation to study the cutting system of the circular saw blade of a mulberry tree cutter and obtained the trends in stress and cutting force, focusing on four factors: the number of teeth, cutting speed, feed speed, and diameter of the circular saw blade [6]. Song et al. investigated the effect of cutting parameters

on the ultimate shear stress and specific cutting energy of sisal blades and obtained the optimal design combination of parameters for the cutting speed, blade inclination angle, blade entry angle, and blade elevation angle [7]. Li et al. investigated the mechanical properties of apple branches and deduced the relationship between the cutting force and the feed rate, cutting linear speed, and branch diameter [8]. In addition, there are a large number of studies on the cutting mechanical properties of sugarcane [9], lemon [10], poplar [11], and other branches and stalks.

The bionic cutter is a major innovation in agroforestry machinery, which improves the performance of the equipment by mimicking the structure and function of natural organisms. Hu et al. designed a straw bionic cutter in which the characteristics of the cutting blade derived from the maxillary part of the East Asian flycatcher and verified the effectiveness of the bionic cutter in reducing the cutting resistance and energy consumption via the discrete element method [12]. Ma et al. designed a bionic cutter inspired by the maxillary mouthparts of the longhorn beetle. The problems of high cutting resistance and severe stubble damage, which are common during alfalfa harvesting, were solved [13]. Tong et al. designed a blade imitating the incisors of bamboo weevil larvae and applied it to a vegetable cutter machine; the blade significantly improved the efficiency of chopping [14]. Tian et al. developed a bionic red flax harvester blade by using the upper jaw of a clouded asp as a bionic prototype through orthogonal tests [15].

In conclusion, scholars have further utilized nature's biological prototypes to significantly improve the performance of agricultural machinery components as compared to optimizing the basic parameters of common blades. However, the design of agroforestry blades mostly focuses on low-speed and small-strain scenarios, and relatively few studies have been conducted to address the high-speed and large-strain problems that occur under impact-cutting mode [16] as well as parameters such as the branch diameter and branching angle. Resolving the above problems would be an effective way to improve the cutting performance and cutting efficiency of pruning machines. In this study, three bionic blades were designed based on the principle of bionics, and their drag reduction principle is explained. Additionally, based on finite element (FEA) numerical simulation technology, the cutting performance of the bionic blades is verified. The cutting performance of the bionic blades was investigated for different branch diameters and branching angles. The bionic blades proposed in this study can reduce the energy consumption of impact cutting while ensuring the quality of pruning.

2. Materials and Methods

2.1. Bionic Blade Design

In this study, three bionic blades were designed for the *Populus tomentosa* pruning robot. Sharks are one of the creatures with the strongest bite, and their teeth are usually sharp and serrated, making them suitable for catching, tearing, and chewing prey. Therefore, scholars often study shark teeth as a prototype for blade bionics [17]. In pruning blade design, a toothed edge angle is used, which aims to increase the local stress and make it easier for the blade to cut into the branch tissues. In this study, shark teeth were used as a prototype when designing a bionic blade, as shown in Figure 1A. It was found through the research that *Autocrates aeneus* have a special mouthpart structure [18], which is curved on the outside of the upper jaws to ensure that the tooth blades have enough strength when biting and cutting. Therefore, a curved edge angle was designed for the pruning blade to further reduce the cutting resistance, as shown in Figure 1B. Woodpeckers' beaks have a sharp shape, making them suitable for pecking at trees for food or building nests [19]. Therefore, a pruning blade with a cross-shaped edge angle was designed to further increase the localized stress, as shown in Figure 1C. The technical drawings for the design of the three bionic blades are shown in Figure 2.

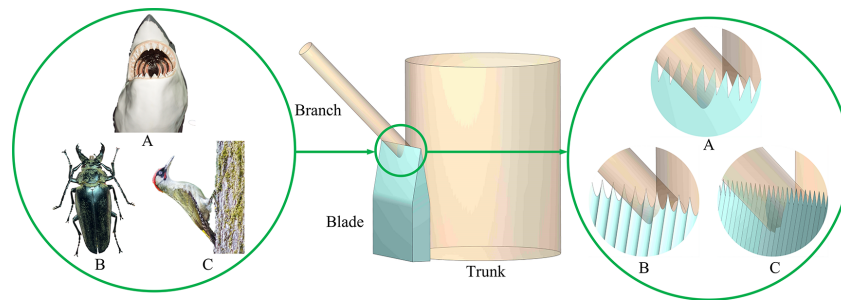


Figure 1. Bionic prototypes and bionic blades. (A) Shark (B) *Autocrates aeneus* (C) Woodpecker.

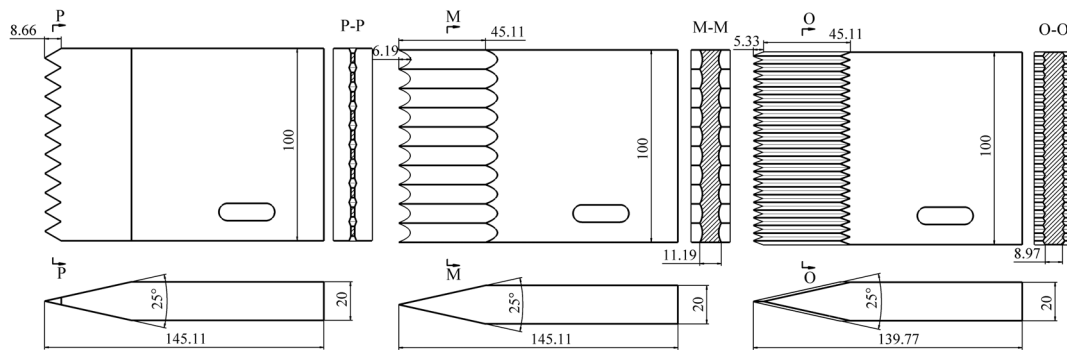


Figure 2. Design technical drawings.

2.2. Mechanical Analysis of Bionic Blade Drag Reduction

As illustrated in Figure 3, when the blade penetrates the branch, the cutting resistance encountered by the blade primarily consists of several forces, including the reaction force F_0 exerted by the branch on the edge as well as the reaction forces F_{1x} , F_{1y} , and friction T_1 applied by the branch on the outer edge surface both in the horizontal and vertical directions. Additionally, there are the reaction forces F'_{1x} , F'_{1y} , and friction T'_1 exerted by the branch on the inner edge surface, which are also in the horizontal and vertical directions.

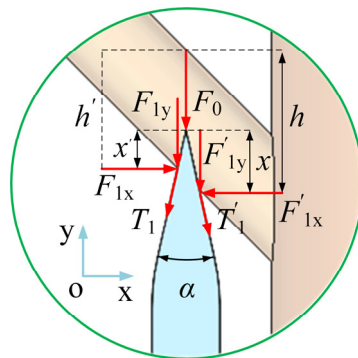


Figure 3. Cutting resistance analysis of the cutting edge.

Utilizing differential thinking and segmenting the outer and inner blade surfaces, the reaction forces dF_{1x} and dF_{1y} on the micro-element of the cutting edge can be expressed as

$$\begin{cases} dF_{1x} = \sigma_1 l dy = \sigma_1 l dx \tan \frac{1}{\alpha} \\ dF_{1y} = \frac{1}{k} \epsilon_y E_y l dx = \frac{1}{k} \epsilon_x \mu E_y l dx \end{cases} \quad (1)$$

where dx is the split micro-element of the outer edge surface in the x -direction, m; dy is the split micro-element of the outer edge surface in the y -direction, m; l is the effective length of the blade, m; σ_1 is the extrusion stress of the branch in the x -direction, N·m²; α is the

wedge angle of the blade, °; ε_y is the strain of the branch in the y -direction above the blade; μ is the Poisson's ratio of the branch; and E_y is the modulus of elasticity of the branch in the y -direction, Pa.

The stress–strain relationship for the branch under extrusion can be modeled using the generalized Hooke's law. Consequently, when the branch is extruded by the outer edge surface, the stress–strain relationship is described as follows:

$$\varepsilon_x = \frac{x}{h} = k \frac{\sigma_1}{E_x} \quad (2)$$

where ε_x is the strain of the branch above the blade in the x -direction, x is the thickness of the branch above the blade extruded by the edge, m; h is the total thickness of the branch above the blade in the x -direction, m; E_x is the modulus of elasticity of the root mass in the x -direction, Pa; and k is the strain transfer coefficient.

Integrating over dF_{1x} and dF_{1y} , the squeezing forces F_{1x} and F_{1y} on the outer edge surface are found to be

$$\begin{cases} F_{1x} = \int_0^x \sigma_1 l \tan \frac{1}{\alpha} dx = \int_0^x \frac{x}{kh} E_x l \tan \frac{1}{\alpha} dx = \frac{x^2 l}{2kh} E_x \tan \frac{1}{\alpha} \\ F_{1y} = \int_0^x \frac{1}{k} \varepsilon_x \mu E_y l dx = \int_0^x \frac{x}{kh} \mu E_y l dx = \frac{x^2 l}{2kh} \mu E_y \end{cases} \quad (3)$$

The friction force T_1 on the outer edge surface is

$$T_1 = \eta \left(F_{1x} \sin \frac{1}{\alpha} + F_{1y} \cos \frac{1}{\alpha} \right) = \frac{\eta x^2 l}{2kh \cos \frac{1}{\alpha}} \left(E_x \sin^2 \frac{1}{\alpha} + \mu E_y \cos^2 \frac{1}{\alpha} \right) \quad (4)$$

where η is the dynamic friction factor between the branch and the edge surface.

Similarly, the various cutting resistances on the inner edge surface are found to be

$$\begin{cases} F'_{1x} = \frac{x'^2 l}{2kh'} E_x \tan \frac{1}{\alpha} \\ F'_{1y} = \frac{x'^2 l}{2kh'} \mu E_y \\ T'_1 = \frac{\eta x'^2 l}{2kh' \cos \frac{1}{\alpha}} \left(E_x \sin^2 \frac{1}{\alpha} + \mu E_y \cos^2 \frac{1}{\alpha} \right) \end{cases} \quad (5)$$

where x' is the thickness of the uncut branch under the blade being extruded, m, and h' is the total thickness of the uncut branch under the blade, m.

The reaction force F_0 at the edge of the blade is

$$F_0 = \delta l \sigma_0 \quad (6)$$

where δ is the edge thickness, m, and σ_0 is the branch ultimate shear stress, $\text{N} \cdot \text{m}^{-2}$.

The total cutting resistance to the blade at the moment of branch breakage is

$$\begin{cases} F_X = F_0 + F_{1x} + T_1 \cos \frac{1}{\alpha} + F'_{1x} + T'_1 \cos \frac{1}{\alpha} \\ F_Y = T_1 \sin \frac{1}{\alpha} - F_{1y} - T'_1 \sin \frac{1}{\alpha} + F'_{1y} \end{cases} \quad (7)$$

where F_X is the total cutting resistance of the blade in the x -direction, N, and F_Y is the total cutting resistance of the blade in the y -direction, N.

In summary, the blade cutting resistance is mainly related to F_0 , F_{1x} , F'_{1x} , T_1 , T'_1 , F_{1y} , and F'_{1y} . Compared with the normal blades, the three bionic blades reduced the contact area when cutting into the branch, which resulted in a reduction in F_0 . However, for the A-type blade, the contact area between the root of the tooth and the branch increased after cutting into the branch, increasing to F_0 . For F_{1x} , F'_{1x} , F_{1y} , and F'_{1y} , the A-type blade behaved the same as the normal blade, while the B-type and C-type blades reduced the reaction force on the outer edge surface by disintegrating the force on the blade surface.

For T_1 and T'_1 , type A blades behave the same as normal blades, while type B and C blades have a corresponding increase in friction due to the increase in friction area. Therefore, only through mechanical analysis can the trend of the relevant partial force be determined; it is difficult to determine the specific value of the total cutting resistance, which needs to be further explored through the method of subsequent experiments.

2.3. Simulation Modeling

The 3D models of the trunk, branches, and blades were constructed using SolidWorks software (version 2022, SolidWorks Corporation, Waltham, MA, USA) at a scale of 1:1, and the trunk and branches were simplified to cylinders to reduce the computation time, enhance the quality of meshing, and improve the accuracy of the finite element simulation analysis [1]. Then, the constructed 3D model was imported into the LS-DYNA module of ANSYS/Workbench software (version 2022, ANSYS Inc., Canonsburg, PA, USA) to simulate the pruning process.

The material characteristic parameters of each model component are shown in Table 1. The blade's stiffness is significantly greater than that of the wood, ensuring that the stress on the blade during impact cutting does not surpass its yield limit. Consequently, the deformation of the blade is negligible, allowing it to be modeled as an isotropic rigid body. The mass of the cutting system during impact-cutting will have an impact on the test results. To more accurately reflect real-world conditions, the mass of the cutting system can be adjusted by increasing its density. The trunk, as the support and positioning point of the branch, does not come into direct contact with the blade during the pruning process and can be set as an isotropic flexible body. The branch directly interacts with the blade during the pruning process, and refining the material ontology model can enhance the accuracy of the simulation. The branch is considered as an anisotropic nonlinear fibrous material, and its material ontology model is derived from the previous study utilized for finite element simulation [20]. The impact-cutting pruning process essentially involves a unit material failure defined after a large deformation or stress overload of the branch unit. In this study, the plastic strain failure model was selected to characterize the branch fracture behavior. This model describes the plastic deformation of the material when the plastic strain surpasses a certain threshold, leading to material rupture as the plastic strain increases further. The critical plastic strain level was set at $\varepsilon = 0.056$ [16].

Table 1. Simulation of material properties.

Geometrical Structures	Density $\rho/(\text{kg}\cdot\text{m}^{-3})$	Young's Modulus E/ GPa		Poisson's Ratio		Shear Modulus G/ GPa	
Blade [21]	5.42×10^5	200.00		0.3		76.9	
Trunk [20]	639.32	2.00		0.3		7.5	
Branch [16]	605.14	E_x	0.25	μ_{xy}	0.68	G_{xy}	0.07
		E_y	0.25	μ_{yz}	0.20	G_{yz}	0.05
		E_z	0.93	μ_{xz}	0.20	G_{xz}	0.05

A reasonable layout of grid cell distribution and size can reduce the amount of calculation and improve the calculation accuracy. Each part of the pruning model is divided by hexahedral mesh, and the free surface mesh is of the type dominated by quadrilaterals and coexisting with quadrilaterals and triangles. The cell size of the trunk part is adjusted to 6 mm, and the cell size of the blade part is 8 mm. The main stresses, strains, and failures are concentrated in the branches, and to facilitate the analysis of the pruning mechanism, the cell size of the branches is adjusted to 3 mm, and the mesh is encrypted in the pruning part. A total of $51,229 \pm 3218$ nodes and $58,663 \pm 2392$ cells were finally generated. The average grid quality rating factor was 0.88 ± 0.06 .

To simulate the actual tree growth state, fixed supports are applied to the bottom surface of the trunk, and the contact surfaces of the branches and the trunk are connected using fixed vice connections. The branch model can be considered as a cantilever beam model. During the pruning process, the blade undergoes translational motion solely along

the positive direction of the z-axis, and it is necessary to impose rigid body constraints on the blade to restrict the degrees of freedom in other directions. Add a velocity of v to the blade along the z-axis according to the realized working condition. To visualize the fracture process of the branch, we modify the contact characteristic type to erosion. Additionally, we include a contact tracker along the z-axis to detect the contact force between the blade and the branch in real time. During the pruning process, the blade cutting the tree trunk encounters frictional resistance. It is necessary to define the geometry interaction that globally accounts for the friction force, setting the static friction coefficient to 0.531 and the dynamic friction coefficient to 0.467, according to Yang et al. [22].

The deformation process of the branch is the most intuitive characterization of the pruning effect, and the size of the contact force acted by the blade and the branch can be used as a comparative result of the actual test, so the total deformation and the contact force are added as the solution result, respectively, and the simulation time is set to be 0.01 s under the premise of ensuring that the branch is completely cut off, and the solution is carried out on the 6-core CPU of the Intel i5-13600. The simulation process is shown in Figure 4.



Figure 4. Simulation process.

2.4. Simulation Model Validation

2.4.1. Verification Sample

In this study, *Populus tomentosa*, a tree species widely planted in northern China, was used as an example. It was found that initiating pruning when the first round of branches reaches four years of age is most appropriate. To promote the healing of the pruning wounds, the period of pruning should be carried out in the dormant season of the forest trees, ideally in early spring before the trees begin to germinate. Therefore, the branches were taken from Baodi District, Tianjin, China ($39^{\circ}46'33''$ N, $117^{\circ}14'50''$ E), the age of the trees was 5 years, and the time of taking the branches was 1 March 2024. The tested branches had a diameter of 14 ± 1 mm, a branching angle of $65 \pm 3^{\circ}$, and good straightness without pests and obvious defects.

2.4.2. Verification Equipment

The validation equipment utilizes a self-designed and manufactured impact-cutting branch-cutting test platform, as shown in Figure 5. The cutting test platform primarily consists of four parts: the branch cutting mechanism, branch feeding mechanism, data acquisition system, and parameter adjustment parts. The branch cutting mechanism adopts a crank-slider mechanism to convert the rotary motion of the motor crankshaft into the reciprocating motion of the blade, and the cutting blades are machined from structural steel with a surface roughness of Ra0.8. The branch feeding system consists of a pusher motor that feeds the branches fixed to the branch fixture into the cutting system. The measurement and control system uses an S-type force transducer (JLBS-1, Dysensor Ltd., Bengbu, China, range: ± 1000 kg) fixed between the blade and the slider to measure the cutting force, and it utilizes a data acquisition card (MCC-1608G, Chengtec, Shanghai, China, sampling frequency: 250 kS/s) to record the cutting force when cutting the branch.

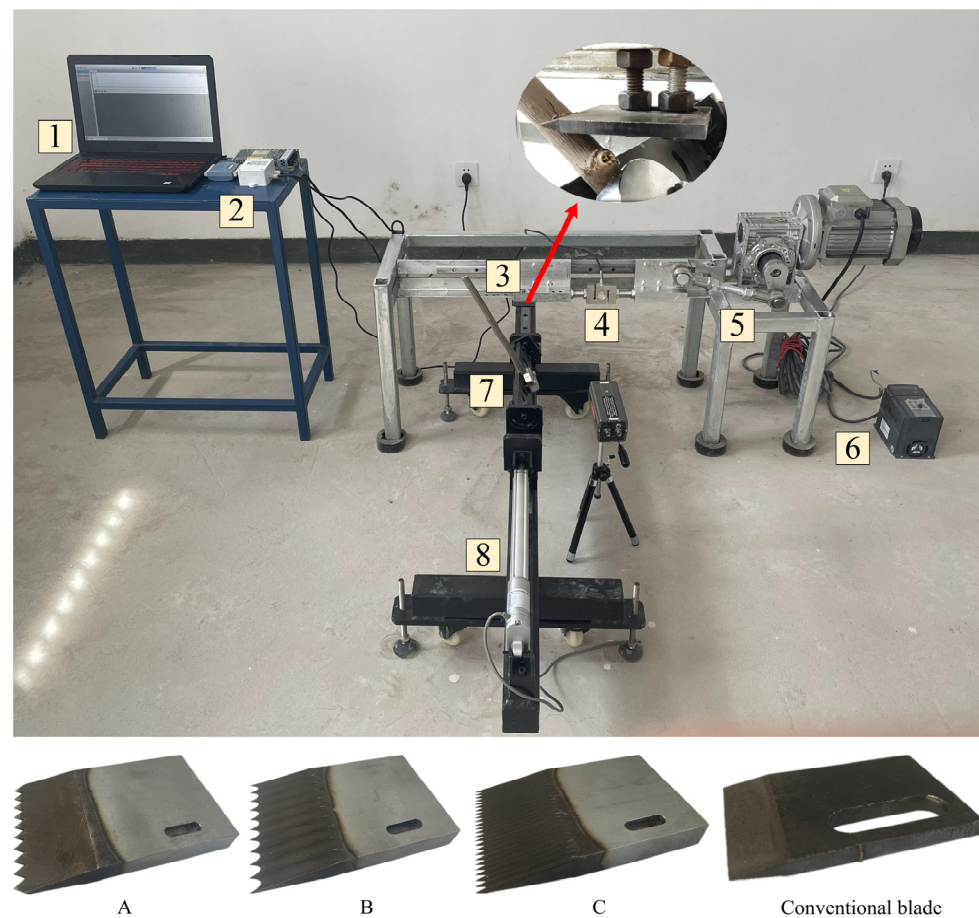


Figure 5. Experimental platform for branch cutting. 1. Laptop computer; 2. Measurement and control system; 3. Experimental blade; 4. Tensile force transducer; 5. Crank-slider mechanism; 6. Frequency converter; 7. Twig fixture; 8. Twig feeding system; (A) Shark's tooth imitation; (B) *Autocrates aeneus*'s mouthparts imitation; (C) Woodpecker's beak imitation.

2.5. Test Indicators and Levels

For pruning equipment, cutting energy consumption directly affects the structural design and power source parameters of the equipment. Therefore, cutting energy consumption E is used as a test index. The size of cutting energy consumption E is determined by the peak cutting force and cutting speed together, as shown in Equation (8).

$$E = v \cdot \int_0^t F(t) dt \quad (8)$$

where E is the cutting energy consumption, J; v is the cutting speed, $\text{m} \cdot \text{s}^{-1}$; $F(t)$ is the cutting force change function, N; and t is the cutting action time, s.

Utilizing the validated finite element model, we examined the mechanism of stress wave propagation during pruning. Additionally, we analyzed how the branch diameter and branching angle influence the cutting energy consumption across various blade types. According to the results of the survey, 91.6% of *Populus tomentosa* branches in the pruning period had diameters D in the range of 10–24 mm, and 87.3% had branching angles θ in the range of 35–70°. Therefore, the test levels were set up as shown in Table 2. The branching angle was set to 45° when conducting cutting experiments with branches of different diameters. The branch diameter was set at 14 mm for the cutting experiments with different branching angles. The experiment was repeated three times under each level, and the average value was taken.

Table 2. Experimental factors and levels.

Level	Branch Diameter <i>D</i>	Branch Angle θ
1	10	35
2	12	40
3	14	45
4	16	50
5	18	55
6	20	60
7	22	65
8	24	70

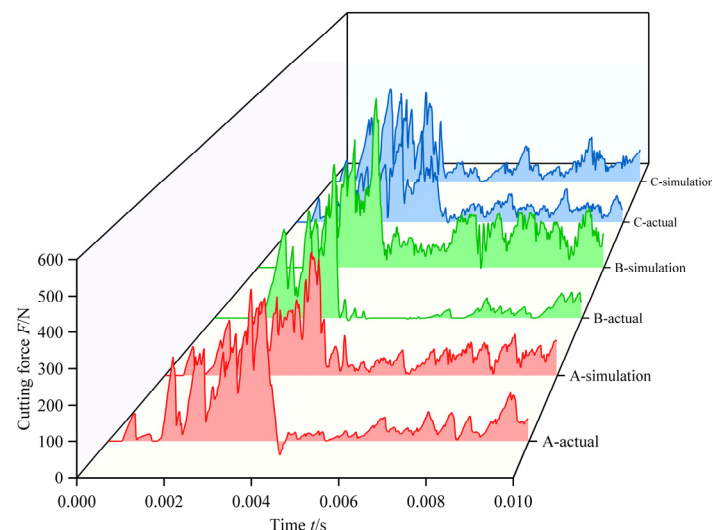
3. Results and Discussion

3.1. Simulation Model Validation Results

Due to the individual differences in the morphology and mechanical properties of the branches, the cutting force–time curves obtained from the simulation do not exactly match the actual test results, but the curves show the same trend. Some of the results of knife verification when cutting branches with a branch diameter of 14 mm and a branching angle of 45° are shown in Figure 6. The relative errors between the simulated cutting force and the corresponding cutting force of the actual test were obtained from Equation (9), in which $\delta_A = 8.24\%$ for the A-type blade, $\delta_B = 7.59\%$ for the B-type blade, and $\delta_C = 12.73\%$ for the C-type blade, and the relative errors were less than 15%, which indicated that the simulation model could be used for the prediction and analysis of the microscopic process of pruning.

$$\delta = \frac{\sum_{i=1}^n |E_s - E_a| / E_a}{n} \times 100\% \quad (9)$$

where E_s is the simulated value of cutting energy consumption, J; E_a is the actual value of cutting energy consumption, J, and n is the number of samples.

**Figure 6.** Verification results.

3.2. Mechanism of Branch Fracture under Stress Wave Action

Solid materials, when subjected to external loads, usually induce three-dimensional stress wave propagation within the structure. The propagation, reflection, and interaction of the stress wave manifests itself as a microscopic response of the internal material. When the lower surface of the branch is subjected to a cutting force, the biological tissue in direct contact with the blade generates acceleration and leaves the initial equilibrium position to undergo compressive deformation. The tissue adjacent to the already deformed area is further subjected to forces exerted by the neighboring parts. Due to inertia, the motion of

the adjacent tissue lags behind that of the tissue in contact with the blade. As a result, the perturbation caused by the cutting force at the cutting position propagates gradually from near to far in the branch, forming a stress wave.

The stress wave propagation law of the pruning process is shown in Figure 7; under the action of cutting load, a compression wave is generated inside the branch. When this compression stress wave reaches the upper surface of the branch, it reflects as a tensile wave. This behavior is analogous to the stress wave propagation mechanism observed under explosive loads. [23,24]. At the same time, due to the upward displacement of the branch cutting point organization, resulting in the formation of tensile waves on the lower side and compression waves on the upper side of the branch near the trunk end, the branch near the trunk end is subjected to the joint action of a variety of stress waves, resulting in large stress. According to the principle of the cantilever beam, the free end of the branch is simultaneously subjected to gravity and cutting force, resulting in a compression wave on the lower side and a tensile wave on the upper side of the free end. Therefore, the free end of the branch will oscillate during the pruning process.

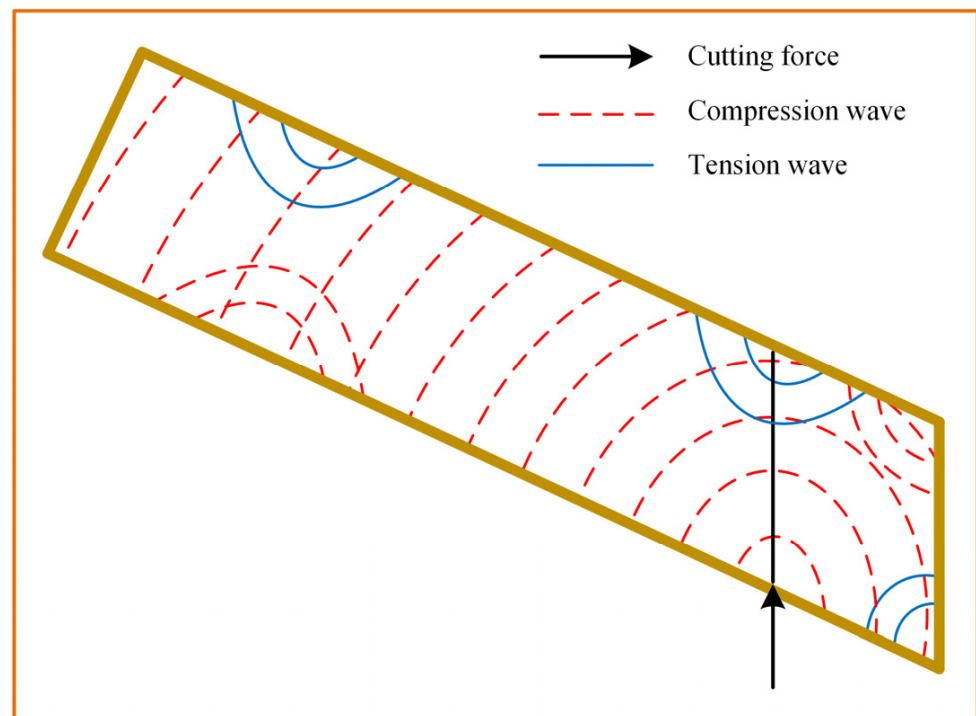


Figure 7. Law of propagation of stress waves.

Numerical simulation revealed a consistent pattern, which was exemplified by a branch diameter of 14 mm and branch angle of 65° . Figure 8 illustrates the propagation of the von Mises stress wave. At 0.0008 s, the blade applies a compressive force on the branch tissues, initiating a compression wave. This wave gradually propagates to the upper surface of the branch, where it generates a reflected tensile wave at 0.0016 s. Between approximately 0.0024 and 0.0028 s, as the branch undergoes global deformation, the bending moment at the near-trunk end of the branch increases, leading to the generation of compression and tension waves. Simultaneously, due to the hysteresis of the movement of the free end of the branch, corresponding tensile and compression waves were also generated on the upper and lower surfaces. Before the branch cracked, the stress peaked at about 0.0058 s, resulting from the superposition of multiple waves. After 0.0064 s, the branch broke and the various waves gradually disappeared. Overall, when the stress at the cutting point of the branch or the bonding point with the trunk is greater than the yield limit of the biomass, the branch will crack at the cutting point or the bonding point with the trunk, which is different from the damage mechanism of circular sawing [25]. The stress at the cutting point under cyclic

load is significantly greater than that under single load, making it easier to reach the yield limit at the cutting point. Therefore, to ensure effective cutting, it is crucial to investigate biomimetic blade designs aimed at reducing energy consumption during cutting under a single load.

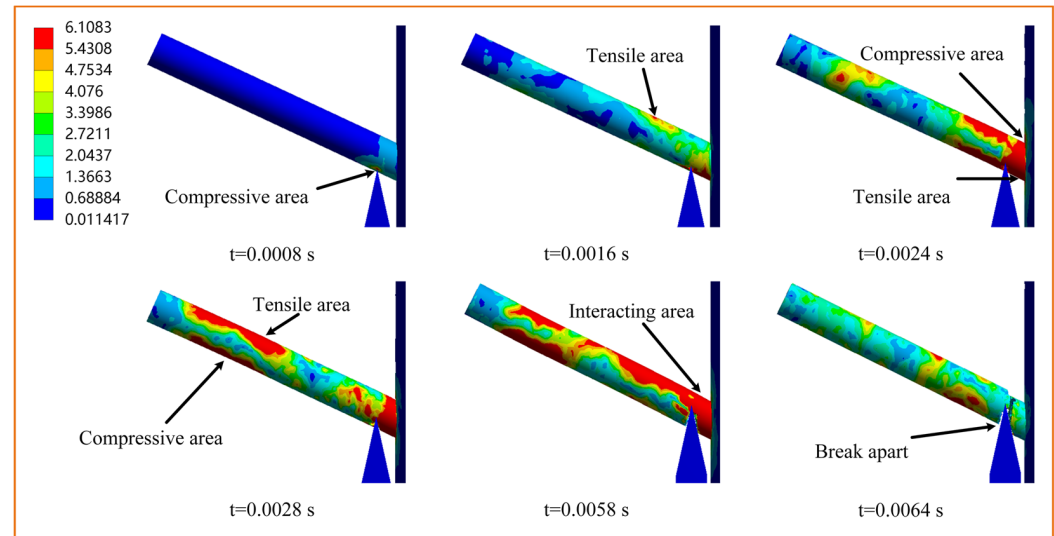


Figure 8. Simulation of stress wave propagation.

3.3. Cutting Performance Analysis of Bionic Blades

3.3.1. Effect of Diameter on Cutting Performance

The effect of different branch diameters on the cutting energy consumption of various blade types is shown in Figure 9, and the von Mises stress cloud of the partial cutting effect is shown in Figure 10. Overall, the cutting energy consumption increases with branch diameter, and this increase becomes more pronounced as the diameter grows; this is because the branch yield limit rises exponentially with the increasing diameter. For branches with smaller diameters, the difference in cutting energy consumption between various blade types is minimal. This is because the branch–trunk bond reaches the yield limit of the biomass before the branch itself, resulting in negligible cutting effects from all blade types on the branch. For different branch diameters, the performance of A-type blades in pruning is more moderate compared to conventional blades. However, A-type blades show excellent performance in turning finishing [26] and rock cutting [27] applications, because the metal and rock materials exhibit strong plastic behavior. The lateral forces generated when the blade cuts into metal or rock cause the material to separate, leading to the blade maintaining contact with the material solely at the edge. In the field of pruning, branches as a kind of elastic–plastic material [28]; when the tip of the tooth cuts into the branch, the branch will not break the first time. With the cutting process, the root of the tooth will cause a relatively large cutting resistance, resulting in the overall power consumption of cutting being higher than that of traditional blades. Both B-type and C-type blades can reduce cutting energy consumption with only a small difference in their effectiveness. This suggests that the design of B-type and C-type blades is particularly well suited to the specific requirements of the pruning field.

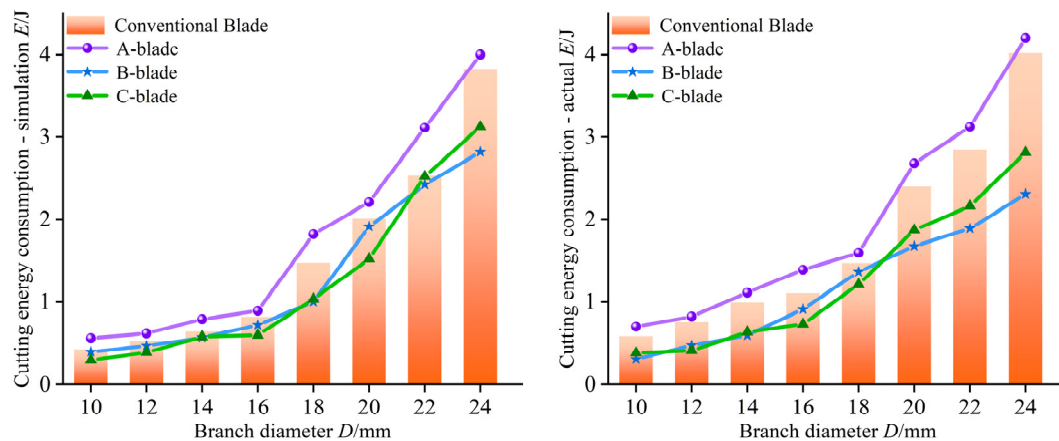


Figure 9. Effect of diameter on cutting energy consumption.

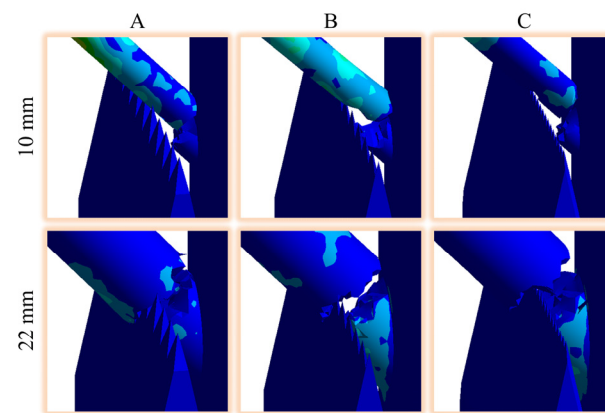


Figure 10. Cutting effect of different diameters. (A) Bionic shark blades; (B) Bionic *autocrates aeneus* blades; (C) Bionic woodpecker blades.

3.3.2. Effect of Branching Angle on Cutting Performance

The effects of different branching angles on the cutting energy consumption of various blade types are shown in Figure 11, and the von Mises stress cloud of the partial cutting effect is shown in Figure 12. As the branching angle increases, the cutting energy consumption decreases. Smaller branching angles are more likely to result in breakage at the branch–trunk bonding point, whereas larger branching angles bring branches closer to complete cutting. Type A blades result in higher cutting energy consumption across all branching angles, whereas type B and C blades significantly reduce energy consumption compared to conventional blades. This reduction is attributed to the cutting state of the bionic tooth edge, which enhances the sliding effect. The presence of this sliding effect reduces cutting resistance and improves the overall cutting efficiency.

To summarize, the average cutting energy consumption of an A-type blade increases by 14.4%, the average cutting energy consumption of a B-type blade decreases by 18.2%, and the average cutting energy consumption of a C-type blade decreases by 16.3%. The A-type blade has a larger cutting resistance, which is not suitable to be applied in the field of pruning, whereas B-type and C-type blades have a greater advantage in the reduction of resistance and consumption. The experimental results also refine the results of the mechanical analysis of insert drag reduction, where the increase in F_0 at the root of the tooth is the main factor leading to an increase in cutting energy consumption for type A inserts, and the increase in T_1 and T'_1 has a lesser effect on cutting energy consumption for type B and C inserts.

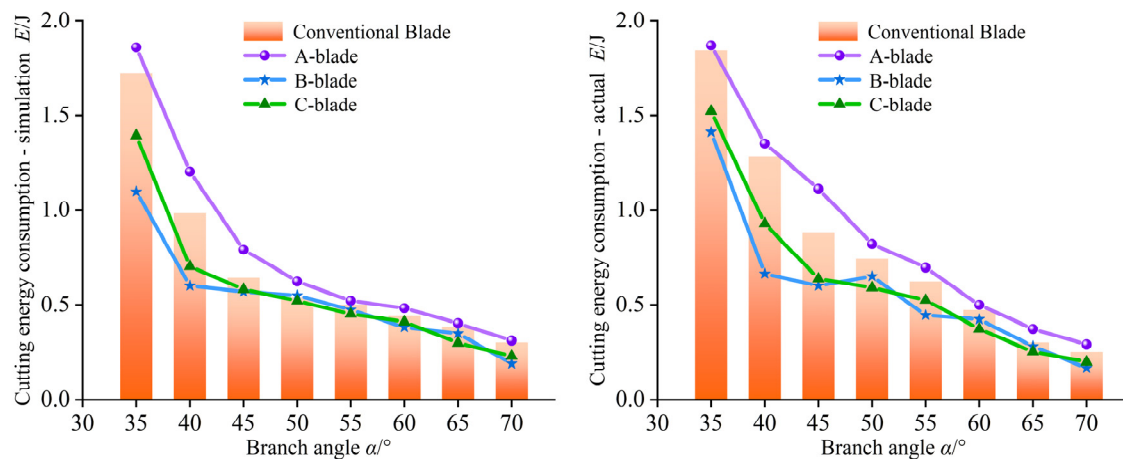


Figure 11. Effect of branch angles on cutting energy consumption.

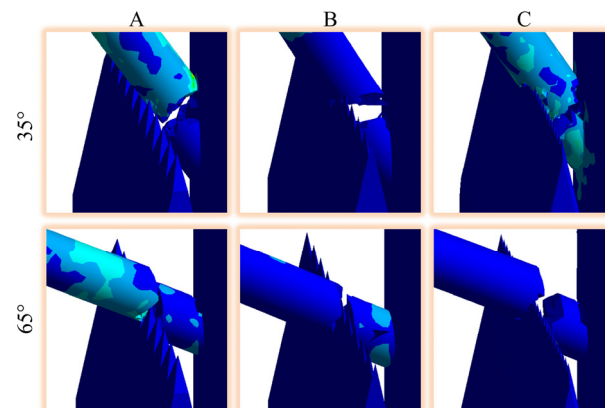


Figure 12. Cutting effect of different branch angles. (A) Bionic shark blades; (B) Bionic *autocrates aeneus* blades; (C) Bionic woodpecker blades.

3.3.3. Actual Cutting Effect

To demonstrate the performance of the bionic blades, a cutting test was conducted using the cutting test rig depicted in Figure 5, and some of the results are presented in Figure 13. Criteria for evaluating the effectiveness of fracture were introduced based on previous studies [29]. Under the action of impact cutting force, the branch undergoes cutting behavior first and then splitting behavior. The percentage value of the split portion of the branch is used as an evaluation index. The statistical results of the percentage of splitting of the three bionic blades are shown in Figure 14. From the test results, it can be seen that type A blades are more likely to cause branch splitting, and type B and type C blades cut down branches with less splitting. In practical applications, considering the relatively complex machining process of the curved surface of the B-type blade, the C-type blade is more advantageous in terms of cost-effectiveness. Overall, the bark remains after cutting, and the flatness of the cut section is inferior compared to the shear effect. Therefore, it is necessary to optimize the simulation model to further consider the influence of the wood structure in subsequent studies. Additionally, continued optimization of the bionic blade structure is essential to improve the quality of the cutting section.



Figure 13. Actual cutting effect. (A) Bionic shark blades; (B) Bionic *autocrates aeneus* blades; (C) Bionic woodpecker blades.

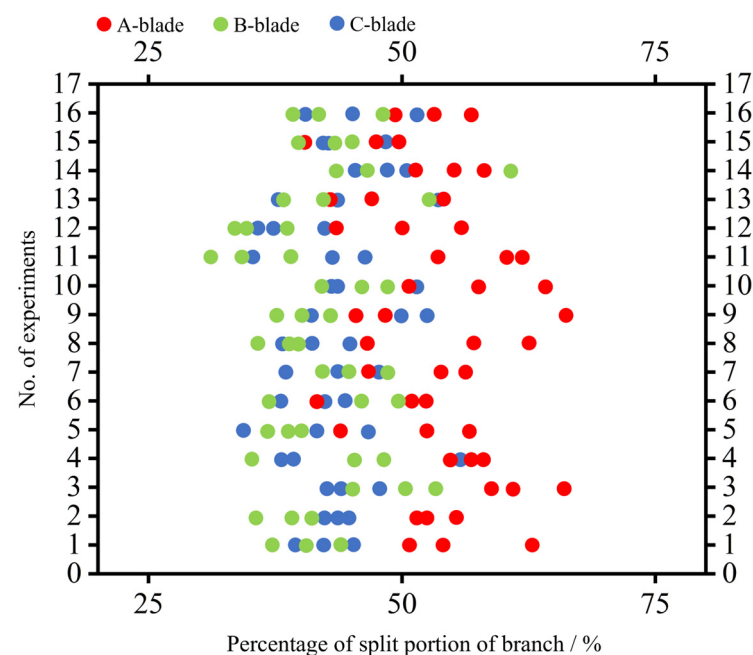


Figure 14. Fracture mode statistics results.

4. Conclusions

In this study, three bionic blades were designed based on the principles of bionics, and the principle of drag reduction was explored. A finite element model of the pruning process was constructed, and its accuracy was verified by comparing it with the actual test results. The stress wave propagation mechanism of the pruning process was investigated using numerical simulation. Additionally, a comparative test was conducted between the three bionic blades and traditional blades. The test results indicate that the cutting energy consumption increases with the increase in branch diameter, and it decreases with the increase in branching angle. The imitation shark-tooth blades exhibited poor cutting performance in pruning application and are not suitable for widespread use. In contrast, the blades with bionic *autocrates aeneus* mouthpieces and pecker beaks have better

cutting performance, reducing the average cutting energy consumption by 18.2% and 16.3%, respectively, compared to traditional blades. These blades meet the requirements for pruning equipment use. The findings provide a significant reference to the technical advancements in pruning and guide the design and improvement of pruning equipment.

In future research, the finite element simulation model will be further extended, and more advanced XFEM technology will be explored to simulate the cutting behavior more accurately. The concentrated stress distribution law of the blade, the wear behavior of the blade, and its optimal design parameters will be further explored.

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