# RESEARCH REGARDING AGRICULTURAL BIONIC BLADE DEVELOPMENT BASED ON THE MECHANISM OF THE CUTTING-SAWING MOTION OF THE CAMPONOTUS MANDIBLE

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# 基于弓背蚁上颚切-锯运动机理的农业仿生刀开发研究

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*DOI: https://doi.org/10.35633/inmateh-73-73*

***Keywords:*** *Bionic blade, cutting-sawing motion, mandible, finite element analysis*

## ABSTRACT

*Aiming at issues such as low instantaneous grasping ability, unsatisfactory cutting quality, and proneness to damage of the blades for existing agricultural mechanical harvesters, by observing the physiological structure and movement characteristics of the ant's mandible and by bionic design theory, a bionic blade was designed and a study was performed to optimize its performance. In this paper, Camponotus ant species was selected as the research object to observe the movement of the right mandibular teeth. It was concluded that the movement of the ant's mandibular teeth has a cutting-sawing motion. A comparative analysis was carried out using the flat blade and the mandibular teeth blade, uncovering that the mandibular teeth movement formed a sliding cut with a variable sliding cutting angle. The mandibular teeth were beneficial for clamping the target and boosting the instantaneous grasping force. The fourth tooth of the mandible was selected as the bionic prototype, from which the contour curve was extracted and analyzed, followed by the design of the bionic blade. Through the finite element method, the influence laws of parameters such as the tooth pitch, structural angle, and blade inclination angle on the stress field and deformation of the bionic blade were analyzed under two force application circumstances: along the inclination direction of the tooth edge and on the blade face direction. The results showed that when the applied force was along the tooth edge inclination, the total deformation of the bionic blade initially decreased and then increased with the tooth pitch increase. The maximum equivalent stress of the bionic blade rose gradually with the tooth pitch increase, and the total deformation decreased with the increase of the inclination angle of the tooth. The equivalent stress diminished with the rise in the inclination angle. With the increase of the structural edge angle, the total deformation of the bionic blade rose gradually. When the force was applied along the blade face direction, the deformation and stress values of the blade were significantly lower than those when the force was along the tooth edge inclination. The research findings can offer theoretical references for the design of bionic blades for harvesters.*

## 摘要

*针对现有收割机用刀具瞬时抓取能力低、切割质量不理想、刀具易损坏等问题，通过观察蚂蚁上颚生理结构和运动特征，依据仿生设计理论，设计仿生刀刃来优化其性能。本文选取弓背蚁为研究对象，观察右侧上颚齿运动，得出蚂蚁上颚齿的运动为一种切-锯运动。选择平刃与上颚齿刃进行对比研究，得出上颚齿运动过程形成滑切，且滑切角是变化的，上颚齿有助于钳住目标，提高瞬时抓取力。选取上颚第四齿为仿生原型，提取分析上颚齿的轮廓曲线，设计仿生刀刃。利用有限元方法，分析作用力沿着齿刃倾斜方向和刀面方向两种情形下，刀刃齿距、构造刃角和刀刃倾斜角等参数对仿生刀应力场和形变的影响规律。结果表明：当作用力沿齿刃倾斜方向时，仿生刀总变形量随着齿距的增加，呈现先变小后变大趋势，最大等效应力随着齿距增加而呈现逐渐增大趋势；总变形量随着齿刃倾斜角增加，呈现逐渐减小趋势；仿生刀等效应力随着齿刃倾斜角增加，呈现逐渐减小趋势；随着构造刃角增加，仿生刀总变形量呈现逐渐增大趋势。当作用力沿着刀面方向时，刀片形变和应力值都远远小于作用力沿齿刃倾斜方向的形变和应力值。研究结果可为收获机用仿生刀具设计提供理论参考。*

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## INTRODUCTION

During agricultural harvesting processes, the blade acts as the "tooth" of the harvester, and its performance and quality directly determine the working quality of the harvester and the straw treatment effect *(Ren et al., 2023; Zhang et al.,2022)*. The characteristics of crops vary significantly, and the cutting situations are complex *(Guo et al., 2024)*. There are issues such as low instantaneous grasping ability of straw, unsatisfactory cutting quality, and proneness to damage for the cutting knives of harvesters *(He et al., 2023)*. Under the demand of developing a low-carbon, it is of great significance to research and develop high-quality and highly adaptive cutting blades for harvesters.

Bionics is a field that focuses on the complex and refined structures of evolved or coevolved living organisms that are highly adaptable to their environment *(Liang et al., 2016)*. As an interdisciplinary subject, bionics is applied in agricultural machinery research and plays a vital role in enhancing the operational performance of agricultural machinery equipment *(Chen et al., 2021; Yu et al., 2024; Zhao et al., 2023)*. Meanwhile, it can provide new research ideas and methods to improve the performance of crushing blades. By analyzing the geometric shape of the mandible of herbivorous insects, such as crickets and locusts, researchers have extracted the curve of the mandible tooth to design bionic stubble blades and have experimentally demonstrated that such blades can reduce resistance and energy consumption *(Zhao et al., 2020; Jia et al., 2013)*. Tong et al. studied the mouthparts of Cyrtotrachelus longimanus Fabricius and found that the contour curve of the maxillary incisors was close to the standard circular arc. Based on their analysis results, a bionic vegetable cutting blade was designed *(Tong et al., 2017)*. Test results indicated that the designed bionic vegetable cutting blade could significantly reduce energy consumption and effectively improve the cutting. Tian et al. designed a bionic blade based on the morphological characteristics of the mandible cutting teeth of longhorn beetles. Bench test results showed that the designed bionic blade could significantly reduce the maximum cutting force and power consumption *(Tian et al., 2017)*. Du et al. designed three bionic cutting blades based on the mandible shape and structure of crickets. Compared with ordinary cutting blades, the bionic cutting blades are more suitable for cutting tea stalks *(Du et al., 2018)*. In conclusion, analyzing the geometric structure and shape profile of chewing mouthparts of certain insects for bionic crushing blade design has become an effective way to improve the performance of agricultural machinery working parts.

Ants are one of the most widely distributed and numerous insect species on Earth *(Paul et al., 2003)*. They possess a unique and hard mandible structure for carrying food and providing considerable bite force to cut branches and leaves and crush food at high speed *(Ma et al., 2022)*. Ants have well-formed mandible teeth, which are excellent bionic prototypes for designing a new type of crushing blade. The purpose of this study is to clarify the sawing motion characteristics of the right mandibular teeth of ants, elaborate the mechanism of the cutting-sawing motion of the ant's mandible, and provide a basis for the design of bionic blades. By employing the finite element method to analyze the structural parameters and acquire the influence laws of key parameters such as the tooth pitch, the inclination angle, and the structural edge angle on the total deformation, stress, and strain of the bionic blade under different forces, research results can provide a reference for the design of bionic knives for harvesters.

## MATERIALS AND METHODS

### *Analysis of cutting principle of camponotus*

*Camponotus japonicus* (class insect: hymenoptera, formicidae), commonly known as carpenter ant, has a propensity for cutting leaves and exhibits excellent crushing capabilities. Accordingly, *camponotus japonicus* was selected as the research object in this study. The analysis route of the geometric features of mandible is shown in Figure 1.

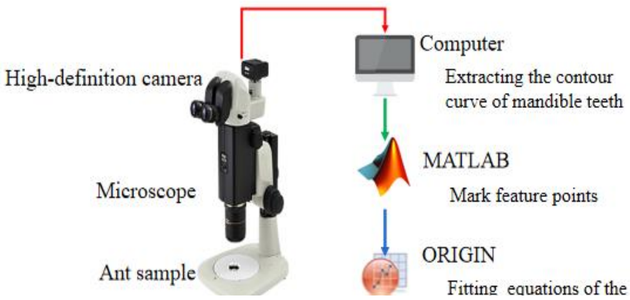



**Fig. 1 - Analysis route of the ant mandible**

The ants analyzed in this study were captured from a corn field in Gaizhou County, Liaoning Province, China. A total ant samples were measured and analyzed. The measurement results of the structural parameters of the samples are presented in Table. Microscope and Image View software were utilized to capture the video of the mandible movement of the ant, and the Free Video software was employed to convert the video into pictures frame by frame. Figure 2 presents the opening and closing process of the ant's mandible. From I to VI, the palate opens, reaching the maximum at time VI, and from VII to XI, the mandible closes.

**Table 1**

**The structural parameters of ants**

| Ant species | Camponotus |
|---|---|
| weight/mg | 15.4±0.30 |
| body length/mm | 11.45±0.30 |
| maxillary length/mm | 1.57±0.18 |
| head width/mm | 3.13±0.27 |
| head length/mm | 3.05±0.35 |

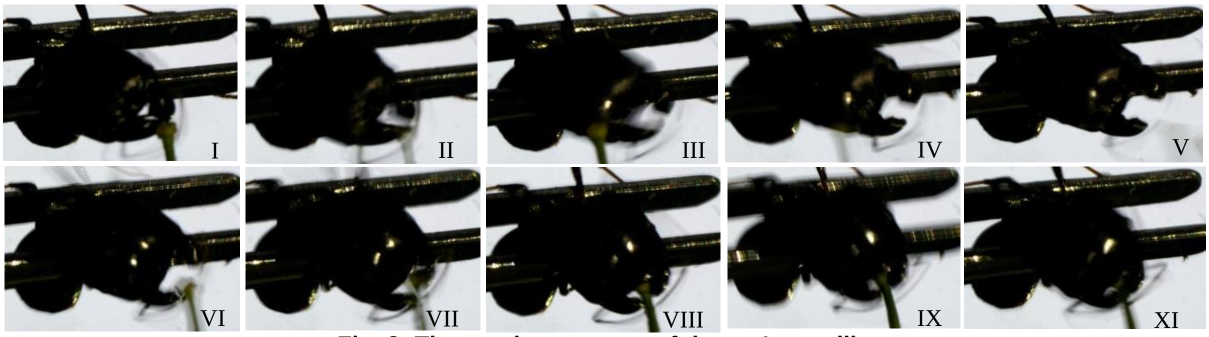
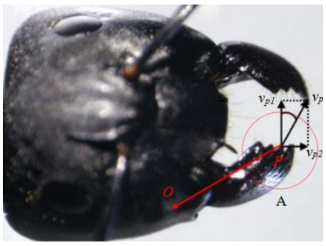
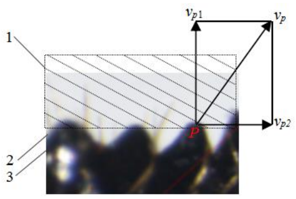



**Fig. 2 -The moving process of the ant's maxilla**

The analysis of the movement of the right maxillary closure is illustrated in Figure 3. The axis of the maxillary motion is positioned at point $O$. The initial point of the cutting force rests at the end point of the maxillary teeth, and the end point of a specific tooth is regarded as point $P$. The movement of $P$ comprises moving to the left side of the upper jaw and the outer side of the oral cavity. The speed of the movement towards the left palate is defined as the cutting speed of the right palate and is denoted by $v_{p1}$, the velocity of the movement away from the outer part of the mouth is designated the sawing velocity of the right upper jaw and is expressed by $v_{p2}$. Consequently, the absolute movement of the maxillary palate is a cut-saw movement.

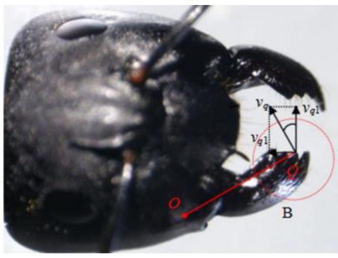


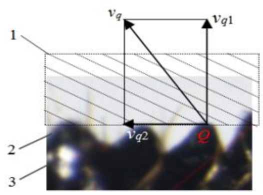




*1.The Object; 2.Maxillary tooth blade; 3.The maxillary tooth*
*Magnified view of Area A*

**Fig. 3 - Analysis of the maxillary moving process distant from the mouthparts**

As shown in Figure 4, the movement process of the maxilla towards the mouth-part is illustrated. The rotation axis of the maxilla movement is at point $O$. The initial application point of the cutting force is at the end point $Q$ of the maxillary tooth. The movement of point $Q$ of the maxillary tooth comprises two parts: approaching the left maxilla and the inner side of the mouth-part.

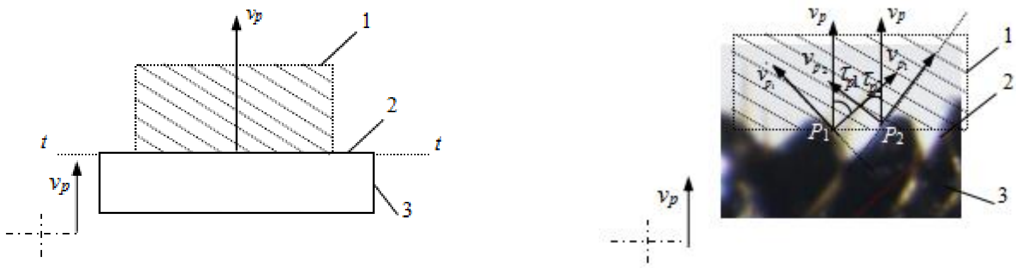



*1.The Object; 2.Maxillary tooth blade; 3.The maxillary tooth*
*Magnified view of Area B*

**Fig. 4 - Analysis of maxillary moving process close to mouthparts**

In order to further investigate the principle underlying the cutting and sawing movement of the mandibular teeth of the ant, a comparative study was carried out between the flat blade and the mandibular blade. As illustrated in Figure 5, the blade cuts the object at a speed of $v_p$, the cutting mode of the flat-blade blade is tangent. When the mandibular blade cuts, the absolute speed of the contact point is $v_p$. Taking the adjacent points $P_1$ and $P_2$, the absolute speed of $P_1$ can be decomposed into the normal direction velocity $v_{p1}$ and the tangential velocity of *the* point $v_{p1}'$. The absolute movement direction of $P_1$ is neither parallel nor perpendicular to the cutting line of the tooth profile, thereby forming a sliding cut. Similarly, point $P_2$ also constitutes a sliding cut on the tooth edge line, and the sliding cutting angle of this point is $\tau_{p2}$. The sliding cutting of the tooth edge of the upper jaw is a type of cut-saw motion.



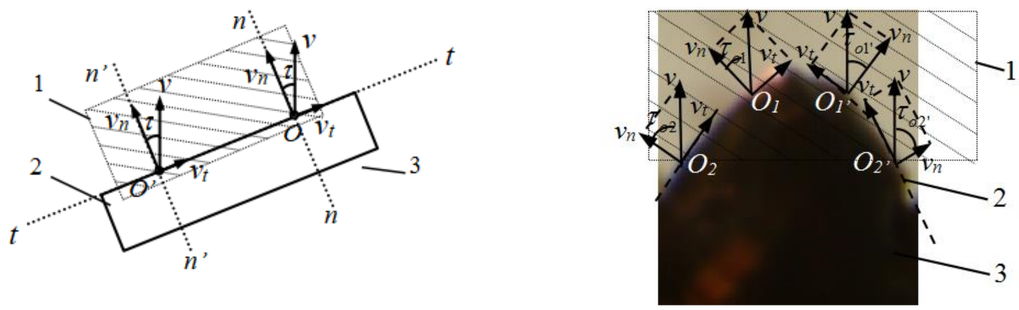

***(a) Flat blade***
*1.The Object; 2.Flat edge; 3.Blade*

***(b) Maxillary tooth blade***
*1.The Object; 2.Maxillary tooth edge; 3.Maxillary tooth*

**Fig. 5 - Comparative analysis of cutting motion between flat and ant mandibular edge**

As depicted in Figure 6, during the cutting process of the object using the flat-edge blade, a sliding cut is formed. The sliding cutting angles at point $O$ and point $O'$ are identical, and the sliding cutting angle of the flat-edge cutting remains fixed. Any section of the curve of the maxillary tooth can be taken to analyze the sliding cutting angle during the cutting process of the bionic edge. At time $t_1$, two points $O_1$ and $O_1'$ on the bionic edge cut the object, and at time $t_2$, two points $O_2$ and $O_2'$ perform the cutting. It is ascertained that the sliding cutting angles of $O_1$, $O_1'$, $O_2$, and $O_2'$ are respectively $\tau_{01}$, $\tau_{01'}$, $\tau_{02}$, and $\tau_{02'}$.

From time $t_1$ to $t_2$, the sliding cutting angle demonstrates an overall increasing tendency. The sliding cutting angle during the cutting process is variable, or the cut-saw motion relationship is dynamically altering. Hence, the maxillary tooth edge of the ant is beneficial for cutting objects and possesses superior cutting performance compared to the flat edge.




*（a）Flat blade*
*1.The Object; 2.Flat edge; 3. Blade*

*（b）Maxillary tooth blade*
*1.The Object; 2.Maxillary tooth edge; 3.Maxillary tooth*

**Fig. 6 - Comparative analysis of slip cutting angle between flat and ant mandibular edge**

Furthermore, the external contour of the maxillary tooth of the ant enables it to have increased contact with the object to be cut during the cutting process, which is conducive to the cutting operation. Through evolution and natural selection, the tooth structure and arrangement of the maxilla of the ant have proved advantageous for both fighting and food processing, and also have significant reference value for the bionic design of the blade in the harvester.

### *Geometrical characteristics of ant mandible teeth*

For morphology measurements, the ant samples were placed in a plastic test tube containing 10 ml of absolute ethanol until they became inactive. In this experiment, the mandible teeth were observed using a research-grade stereo microscope (NSZ818, magnification ranging from 14 to 60, Yongxin Co., Ltd.).

Ants usually crush food with the right mandible, disregarding individual differences. Details of the ant's right mandible are shown in Figure 7. The mandible was observed to have five teeth with a relatively uniform size and distribution, and the tooth exhibited a smooth surface and an arc-shaped profile.

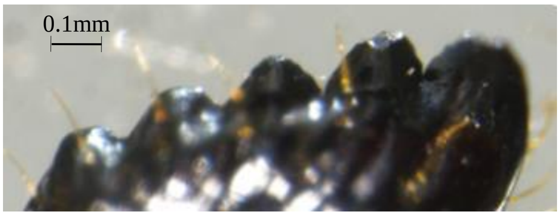



**Fig. 7 - The image of right maxillary tooth**

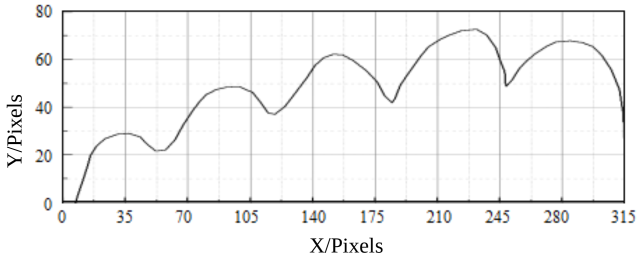



**Fig. 8 - Extracted positive contour curve of maxillary tooth**

Based on the previous research findings of the research group *(Zhao et al., 2022*), the forward boundary contour image and the side boundary contour image of the mandible were provided (as shown in Figure 8), and the mathematical model of the forward contour curve and side profile was established. After analyzing the mathematical model, the structural parameters of the fourth tooth of the mandible of the ant were chosen as biomimetic elements. The tooth size is a significant parameter for the structural characteristics of the mandible. To optimize the structural characteristics of the mandible, the ratio of height $W_0$ to root width W is defined as w. Subsequently:

$$w = \frac{W_0}{W} \tag{1}$$

Where: $w$ is the ratio of height $W_0$ to root width $W$.

The geometric dimensions of the teeth were measured by using an image acquisition system configured with a research-grade stereo microscope NSZ818, as shown in Table 2.

**Table 2**

**The geometric dimension of maxillary tooth**

| Tooth Name | Root Width/μm | Root Height/μm | Ratio of Height to Width |
|---|---|---|---|
| Fourth Tooth | 150.643 | 75.83 | 0.5055 |

Because the actual size of the teeth is extremely small, it is necessary to optimize the structural characteristics of the bionic teeth. The distance values of the bionic blade are 1.5, 3, and 4.5 mm, which are applied in the design of the bionic blade.

### *Construction of the simulation and optimization model of bionic teeth blade*

In order to improve the reliability and accuracy of the results, the bionic blade model was appropriately simplified to evade the influence of blade geometry and other factors *(Liu et al., 2018)*. As for the simplified bionic blade structure model, it is shown in Figure 9.

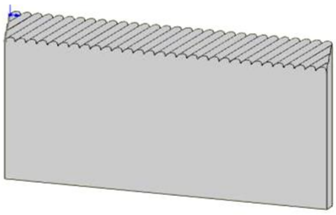


**Fig. 9 - Simplified geometric model of blade**

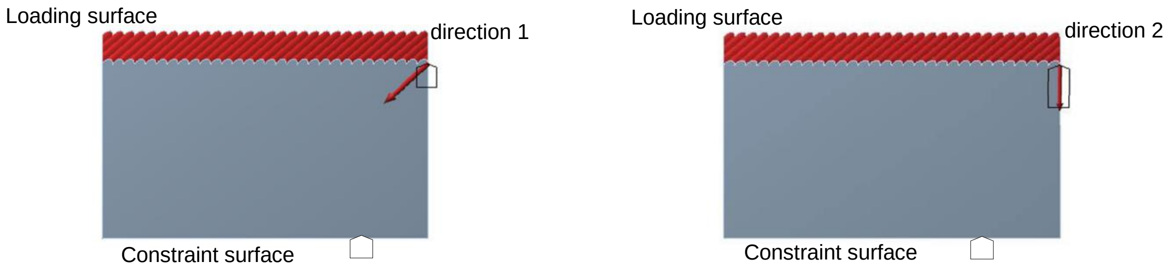
The blade structure angle is set at 26°, the tooth edge is inclined at 15°, the direction of the action force is selected in two ways: along the blade direction and the blade tilt direction, and the tooth pitches of the bionic blade are 1.5, 3, and 4.5 mm respectively, to explore the influence of the bionic blade tooth pitch on the stress field and deformation of the bionic blade.

The blade structure angle is set at 26°, the blade tooth pitch is 3 mm, and the direction of the action force is selected in two ways: along the blade direction and the blade tilt direction. The inclination angles of the teeth are respectively selected as 0°, 7.5°, 15°, 22.5°, 30°, 37.5°, and 45° to explore the influence of the inclination angle of the teeth on the stress field and deformation of the bionic blade.

The blade tooth pitch is set as 3 mm, the inclination angle of the teeth is 30°, and the force direction is selected along the blade direction and the blade tilt direction. The blade structure angle is set at 14°, 20°, 26°, 32° and 38°, to explore the influence of the blade structure angle on the stress field and deformation of the bionic blade.

The material parameters commonly utilized in engineering are offered by ANSYS software, and the material of the blade is selected as steel T10. A variety of distinct mesh division approaches exist in ANSYS software. During this analysis process, Face Meshing division and Body Sizing control are adopted, and ElementSize is specified as 1.0 mm to acquire the finite element mesh model of the blade.

The actual installation mode of the bionic blade is threaded connection. To mitigate the influence of threaded holes on the simulation test results, the threaded holes are omitted in the simplified model, and the opposite edge of the blade is chosen as the fixed constraint application surface. Neglecting air friction, a uniform load is applied to the blade, the maximum load on the simplified bionic model is set at 2000 N, and the loading is static *(Xue et al., 2016)*. The load direction is classified into the direction along the tooth edge inclination (referred to as direction 1) and the direction along the blade surface (referred to as direction 2), as shown in Figure 10.




*(a) Force along the tilt of the tooth edge* *(b) Force along the tool face*

**Fig. 10 - Diagram of constraints and loads**

## RESULTS AND ANALYSIS

### *Analysis of the Influence of Tooth Pitch Parameters on the Deformation and Stress Field of the Bionic blade*

The effect of teeth pitch parameters on the deformation and stress field of the bionic blade is shown in Figure 11, 12, 13.

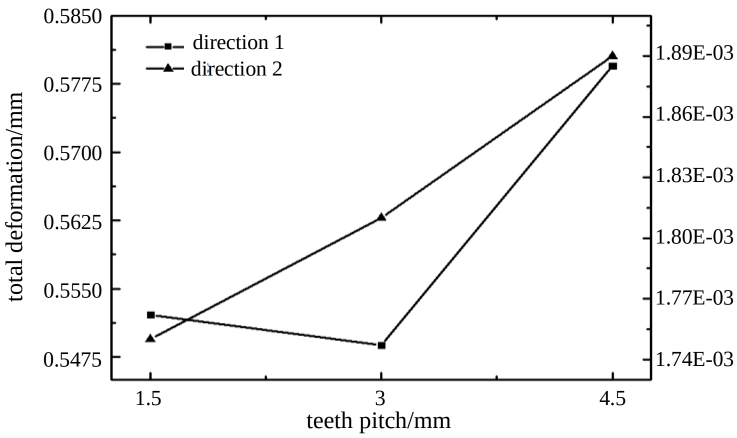



**Fig. 11 - Rule of total deformation of blade with teeth pitch**

As illustrated in Figure 11, when the force is applied along direction 1, the total deformation of the bionic blade exhibits a trend that initially decreases and subsequently increases with the increase of the tooth pitch.

The total deformation of the bionic blade with a 3 mm tooth pitch amounts to 0.54878 mm, representing a 5.3% reduction compared to that of a 4.5 mm tooth pitch. When the force is applied along direction 2, the total deformation of the bionic blade rises in tandem with the increase in the tooth pitch. The total deformation of the bionic blade with a tooth pitch of 4.5 mm escalates by 7.67% when contrasted with that of a 1.5 mm tooth pitch. By comparing the total deformation of the blade under the two conditions, it is discovered that the total deformation of the blade along direction 1 is considerably larger than that along direction 2.

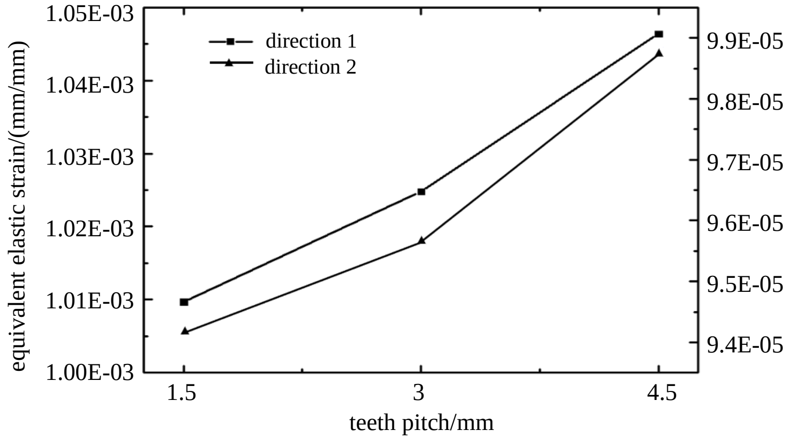



**Fig. 12 - Rule of equivalent elastic strain of blade with teeth pitch**

As can be discerned from Figure 13, when the force is applied in both direction 1 and direction 2, the equivalent strain of the bionic blade gradually ascends with the increase in tooth pitch. When the force is applied along direction 1, the equivalent strain of the bionic blade with a tooth pitch of 1.5 mm reaches $1.0097 \times 10^{-3}$, and the equivalent stress of the bionic blade is reduced by 3.5% in comparison with that of a 4.5 mm tooth pitch. When the force is applied along direction 2, the equivalent strain of the bionic blade with a 1.5 mm tooth pitch amounts to $9.4171 \times 10^{-5}$, and the equivalent stress of the bionic blade is reduced by 4.64% when compared to that of a 4.5 mm tooth pitch.

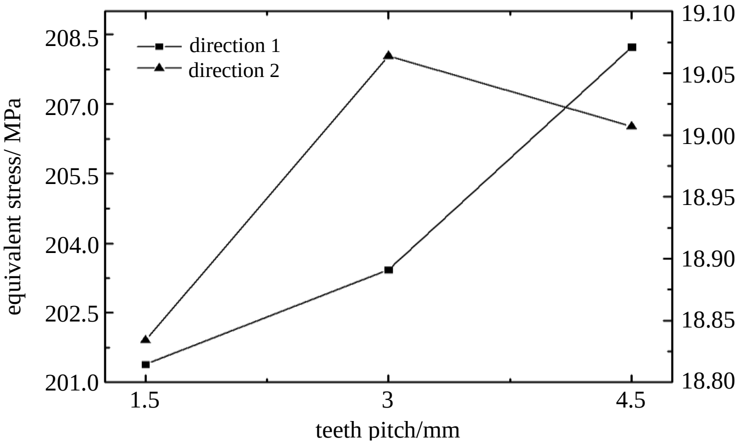



**Fig. 13 - Rule of equivalent stress of blade with teeth pitch**

As can be seen from Figure 13, when the force is applied along direction 1, the maximum equivalent stress of the bionic blade gradually increases with the increase in tooth pitch. The maximum equivalent stress of a bionic blade with a 4.5 mm blade pitch is 208.23 MPa, which is 3.3% higher than that of a bionic blade with a 1.5 mm blade pitch. When the force is applied along direction 2, the maximum equivalent stress of the bionic blade initially increases and subsequently decreases with the increase in the tooth pitch. The maximum equivalent stress of the bionic blade with a 3 mm tooth pitch is 19.064 MPa, and the maximum equivalent stress of the bionic blade is increased by 1.2% compared to that with a 1.5 mm tooth pitch.

***The influence of the inclination angle of the tooth on the deformation and stress field of the bionic cutter***

Figures 14, 15, and 16 show the effect of the inclination angle of the tooth on the deformation and stress field of the bionic blade. As can be seen from Fig. 14, when the force is applied along direction 1, the total deformation of the bionic blade gradually decreases as the inclination angle of the tooth edge increases. The total deformation of the bionic blade at an inclination angle of 45° of the tooth is decreased by 29.31% compared with that at 0°. When the applied force is along Direction 2, the total deformation of the bionic blade initially increases and then decreases with the increase in the inclination angle of the tooth. When the inclination angle of the tooth is 30°, the total deformation of the blade is 1.818×10$^{-3}$ mm.

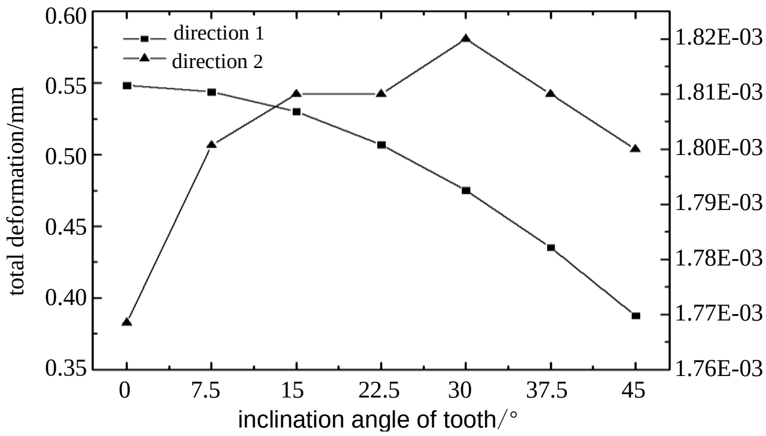



**Fig. 14 - Rule of total deformation of blade with inclination angle of tooth**

As can be observed from Figure 15, when the force is applied along Direction 1, the equivalent strain of the bionic blade gradually decreases with the increase in the inclination angle of the tooth. The equivalent strain of the bionic blade with a tooth inclination angle of 45° is reduced by 13.77% compared to that of the bionic blade with a tooth inclination angle of 0°. When the applied force is in Direction 2, the equivalent strain of the bionic blade initially decreases and then increases with the increase in the inclination angle of tooth.

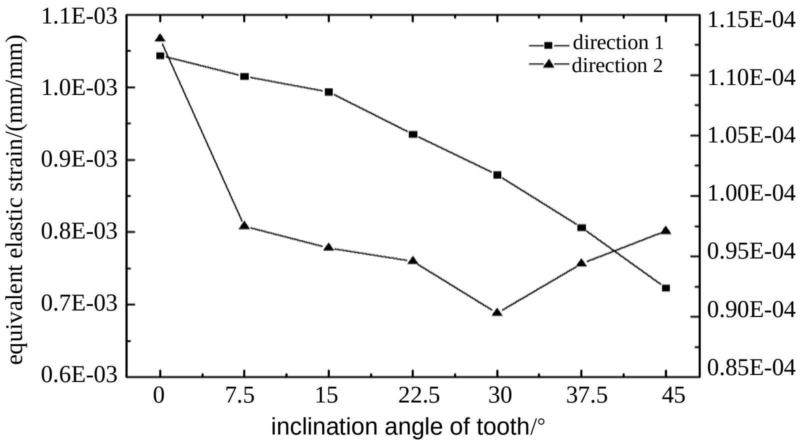



**Fig. 15 - Rule of equivalent elastic strain of blade with inclination angle of tooth**

As can be seen from Figure.16, when the force is applied along Direction 1, the equivalent stress of the bionic blade gradually decreases with the increase of the tooth inclination angle. The equivalent stress of a bionic blade with a 45° tooth inclination angle is 144.23 MPa, which is 30.16% less than that of a bionic blade with a 0° tooth inclination angle.

When the applied force is along Direction 2, the total deformation of the bionic blade initially decreases and then increases with the increase in the tooth inclination angle. Among them, when the tooth inclination angle is 22.5°, the maximum equivalent stress of the blade is the minimum, being 17.706 MPa.

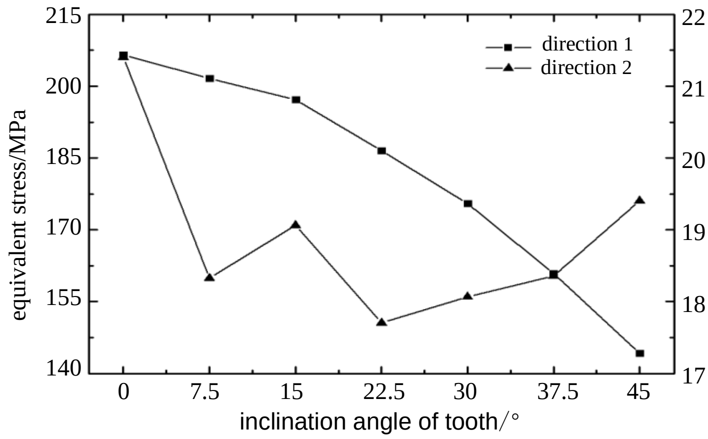



**Fig. 16 - Rule of equivalent stress of blade with inclination angle of tooth**

***Effect of structural Angle of bionic blade on deformation and stress field***

The influence of the structural edge Angle on the stress field and deformation of the bionic blade is shown in Figure 17, 18 and 19.

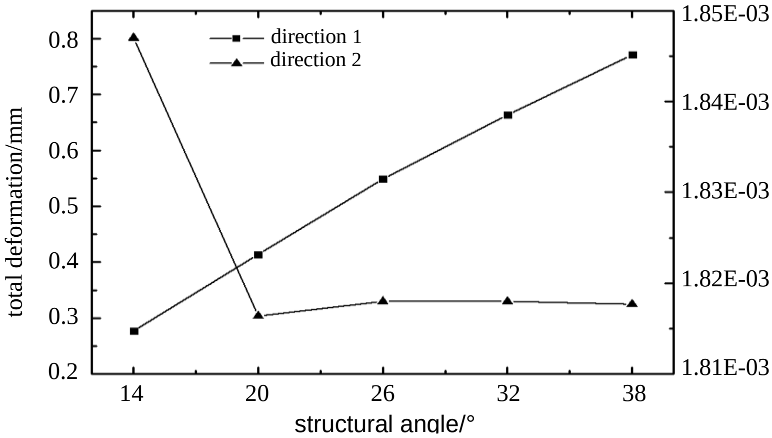



**Fig. 17 - Rule of total deformation of blade with structural angle**

As the force is along Direction 1, with the increase of the structural edge angle, the total deformation of the bionic blade shows a gradual increasing trend. The total deformation of the structural edge angle of 38° is increased by 64% compared to that of 14°. As the force is along Direction 2, with the increase of the structural edge angle, the total deformation of the bionic blade exhibits a trend of rapid decline initially and then basically maintains a stable tendency.

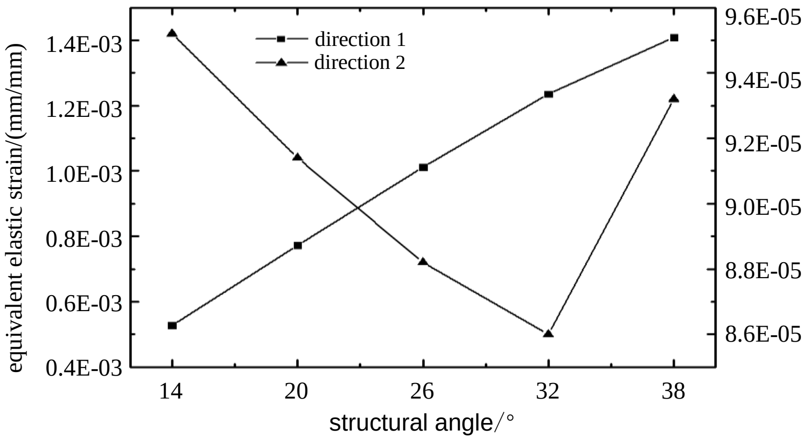



**Fig. 18 -Rule of equivalent elastic strain of blade with structural angle**

When the force is along Direction 1, the equivalent strain of the bionic blade shows a gradual increase with the increase in the structural edge angle, and the equivalent strain of the 38° structural edge angle is 64% higher than that of 14°. When the force is along Direction 2, with the increase in the structural edge angle, the equivalent strain of the bionic blade shows a trend of first decreasing and then increasing rapidly. The equivalent strain of the blade with a 32° structural edge angle is the smallest, which decreases by 9.6% compared to that of 14°.

As the force is along Direction 1, with the increase of the structural edge angle, the maximum stress of the bionic blade shows a gradual increasing trend, and the total deformation of the 38° structural edge angle is increased by 62.4% compared to that of 14°. As the force is along Direction 2, with the increase of the structural edge angle, the total deformation of the bionic blade presents a trend of rapid decline at first and then basically stabilizes. The maximum equivalent stress is minimum when the structural edge angle is 32°, and it is 14.8% less than that of the 14° blade.

The total deformation, equivalent strain, and equivalent stress values of the bionic blade vary significantly when the force is applied in Direction 1 and Direction 2. The deformation and stress values of the blade when the force is along Direction 2 are much smaller than those when the force is along Direction 1.

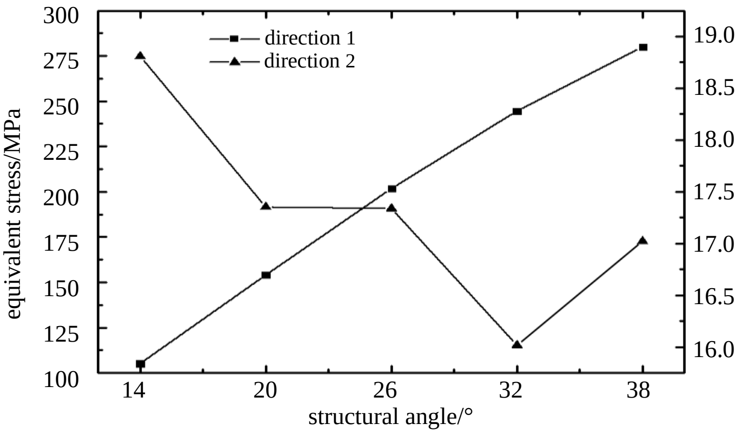



**Fig. 19 -Rule of equivalent stress of blade with structural angle**

## CONCLUSIONS

In this study, the movement and the geometric structure of the mandible teeth of ants were studied, and the characteristic profiles of tooth-4 were utilized in the design of a bionic blade. The models of the blade were developed for analyzing the parameters of the bionic blade through ANSYS. Based on the simulation test results, the following conclusions are drawn.

(1) The movement characteristics of the ant's mandible were studied using research-grade microscopes and high-speed photography techniques. It was clarified that the right maxillary teeth of the ant demonstrated a cutting movement approaching the left maxilla and a sawing movement towards the side of the mouthparts (or away from the side of the mouthparts) during the cutting process. The combined effect of the cutting and sawing movements of the ant's maxillary teeth revealed the tooth-edge cutting mechanism of the cutting-sawing movement of the ant's mandible.

(2) The bionic blade was designed with the following parameters: tooth pitch of 1.5 mm, 3 mm, and 4.5 mm; tooth edge inclination angle ranging from 0 to 45°; and structural edge angle ranging from 14 to 38°. Based on the finite element analysis of the bionic blade structural parameters, the influence laws of the tooth pitch, the inclination angle of the blade edge, and the structural edge angle on the total deformation, stress, and strain of the bionic cutter were obtained. Based on the finite element analysis of the structural parameters of the bionic blade, the influence laws of the tooth pitch, the inclination angle, and the structural edge angle on the total deformation, stress, and strain of the bionic blade were obtained.

## ACKNOWLEDGEMENT

This research was funded by the doctoral research project of Liaoning Natural Science Foundation in 2024 (2024-BS-287), the "Enterprise Doctor Dual Innovation Plan of Yingkou City" project in 2023 (YKSCJH2023-015), and the scientific effort of Liaoning Agricultural Technical College (Lnz202216, LnzkA202310).

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