# Design of Bamboo Cutting Mechanism Based on Crack Propagation Principle

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Bamboo is mainly grown in hilly areas, and the harvesting of bamboo basically relies on labor. Moreover, the bamboo is prone to splitting problems during harvesting. To liberate labor and improve work efficiency, the crack propagation principle of bamboo was studied. Based on this study, a new cutting scheme using spiral feed was proposed. Additionally, a new bamboo cutting mechanism was designed. The new cutting mechanism, when installed on a harvesting vehicle, can automatically complete the cutting operation. The cutting mechanism is different from the traditional ones, and it uses four sets of saw blades for spiral feed cutting around the bamboo, which can reduce the splitting probability during the cutting process. Finally, a solid model of the cutting mechanism was built, and the basic movement process was simulated to verify the feasibility of the bamboo cutting mechanism.

*Keywords: Bamboo; Crack propagation principle; Spiral cutting; Bamboo cutting mechanism; Modeling and simulation*

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## INTRODUCTION

Most of the bamboo in the world is distributed in Asia. Bamboo products have a variety of applications, and there are huge differences in the harvesting and application of bamboo (Zhang 1994). Bamboo is prone to splitting problems during harvesting, and the growth environment of bamboo is often complicated, so it is difficult for large machines to enter.

Most of the existing equipment for bamboo harvesting has only one direction of feed. For example, a charged reciprocating saw for bamboo cutting can reduce the work intensity of direct cutting with a machete; however, it is particularly easy to cause bamboo splitting (Yang *et al.* 2013). Zhou *et al.* (2018) designed a combined forest harvester, which integrates multiple functions, but it is large in size and difficult to adapt to complex terrain. Yang *et al.* (2019) designed a new type of V-shaped double cylindrical milling cutter for bamboo harvesting, but its efficiency is low, and it is easy to tear the bamboo skin. Li *et al.* (2020) designed a handheld bamboo forest harvester, which improves the efficiency of harvesting, but it will have insufficient power and easily cause bamboo splitting. The above harvesting methods reduce the labor, but they cannot effectively solve the problem of bamboo splitting in the harvesting process. The present study focused on the principle of bamboo crack propagation. A new cutting method was studied and analyzed. The influence of different cutting parameters on cutting force and power was considered and optimized to verify that this cutting method can effectively reduce the splitting problem in the harvesting process of bamboo. Finally, a specific structure of the cutting mechanism was designed based on this and conducted a preliminary verification.

## EXPERIMENTAL

### Analysis of Bamboo Cutting Characteristics

Bamboo mainly refers to the bamboo culm, which is mainly composed of bamboo outer skin, bamboo inner skin, bamboo meat, and other parts (Yang *et al.* 2006). The diameter at breast height of bamboo is primarily 8 to 12 cm, the maximum diameter can reach 20 cm, and its maximum wall thickness can reach 15 mm. The moisture content and elastic modulus of bamboo are important indexes that affect cutting, in addition to the hardness of the skin. These parameters are related to bamboo age and bamboo cutting position. The older the bamboo, the smaller is its moisture content and elastic modulus. The bamboos selected for harvesting are older and prone to splitting during cutting. Therefore, the splitting problem needs to be solved when designing the harvesting mechanism.

In order to verify the effect of various cutting methods on bamboo splitting, the fracture property of bamboo was analyzed. The crack modes of the material are shown in Fig. 1. There are three modes of crack: Mode I cracks are open type, mode II are cut type, and mode III are tear type cracks. Due to the organizational structure of bamboo, its main crack mode is mode I (Wang *et al.* 2007). That is, bamboo splits mainly under the tensile stress perpendicular to the crack surface.

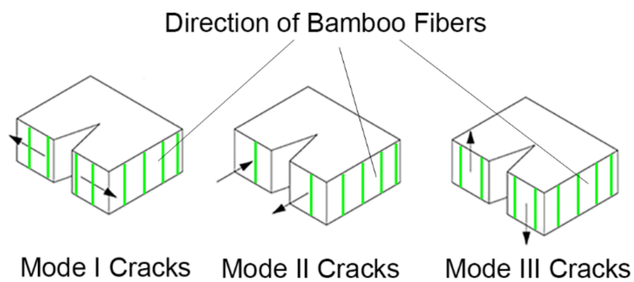


**Fig. 1.** Crack modes of bamboo material

The failure mode of bamboo is governed by its multilayer fiber structure. Tension failure in bamboo fibers could be classified into brittle tension failure, splintering tension failure, and mixed brittle and splintering tension failure. Among these, the fracture mode of bamboo is mainly brittle fracture (Chen *et al.* 2020). When the brittle fracture criterion is used to analyze the splitting of bamboo (Cao *et al.* 2016), the brittle fracture criterion is mainly divided into two types: energy release rate criterion and the stress intensity factor.

According to the criterion of energy release rate, energy will be released when the crack grows. When the crack extends per unit length, the energy released per unit thickness of the pipe is the energy release rate, which is represented by $G$ as shown in Eq. 1,

$$G = \frac{\pi \sigma^2 a}{E} \tag{1}$$

where $\sigma$ is the tensile stress perpendicular to the crack surface (MPa), $a$ is the initial crack length (mm), and $E$ is the elastic modulus of the material (MPa).

The material itself has the ability to resist crack propagation. This ability is called crack propagation resistance and is represented by $R$. When $G > R$, brittle cracks propagate.

According to the criterion of stress intensity factor, the fracture of materials originates from cracks, the strength of stress in crack region is represented by the *K*. For type I cracks, the expression of the stress intensity factor is:

$$K_1 = \sigma\sqrt{\pi a} \quad (2)$$

It can be seen from the above two criteria that the energy release rate *G* and the stress intensity factor *K* are positively related to the material breaking. If the value of *G* and *K* is higher than critical value, brittle cracking will occur and then propagate. The tensile stress perpendicular to the crack surface *σ* can be used to determine the probability of bamboo splitting.

## Cutting Process Simulation Based on ANSYS/LS-DYNA

The dynamic simulation of the linear feed and the spiral feed cutting methods was carried out using ANSYS/LS-DYNA software (ANSYS, Inc., Ansys v.15.0, Pittsburgh, PA, USA) to obtain tensile stress perpendicular to the crack surface. The material model MAT_143 was selected to set up the bamboo model (Zhu *et al.* 2016). The simulation used a bamboo specimen with a diameter of 100 mm and a wall thickness of 10 mm. In order to reduce the computing time, a 200 mm bamboo knot was selected for simulation. The mechanical parameters of the bamboo were finally set as follows (Xia *et al.* 2016; Chen *et al.* 2020):

**Table 1.** Table of Mechanical Parameters of Bamboo

| Item | Density (mg/mm$^3$) | Parallel Modulus of Elasticity (GPa) | Vertical Modulus of Elasticity (GPa) | Parallel Shear Modulus (GPa) | Vertical Shear Modulus (GPa) | Parallel Principal Poisson's Ratio |
|---|---|---|---|---|---|---|
| Numerical value | 0.95 | 11.022 | 0.226 | 0.698 | 0.081 | 0.26 |

For simulation, a standard circular saw blade was chosen. The material used was T10 (Bajun Cutting Tool Company, Dongguan, China) with a diameter of 180 mm. The speed of the saw blade in both methods was 1200 r/min at 10 mm/s feed speed. Different from linear feed method, the spiral feed method involves a spiral around the bamboo axis; that is, there were feeds in two directions at the same time, with the radial feed speed of 1.0 mm/s and tangential feed speed of 9.95 mm/s. In order to reduce the computing time, the saw blade was set as a rigid body of density 7.9 mg/mm$^3$, elastic modulus of 210 GPa, and the Poisson's ratio was 0.275.

After the relevant model was established in SolidWorks (Dassault Systemes, SolidWorks 2018, Paris, France), it was imported it into ANSYS for pre-processing. The relevant element type and material were then set up, and the model was meshed (Li et al. 2018), as shown in Fig. 2, divided with 4480 units for the bamboo, and 4782 units for the saw blade. The bottom of the bamboo was set to be fully constrained, and corresponding loads were applied. Because the splitting of the bamboo mainly occurs at the beginning of cutting, only a period of time at the beginning of cutting was simulated, and the simulation time was set to 50 ms. As shown in Fig. 2, through the comparison of the stress cloud diagrams of the two cutting methods at the same time, it can be seen that the effective stress on bamboo in the spiral feed cutting method was smaller.

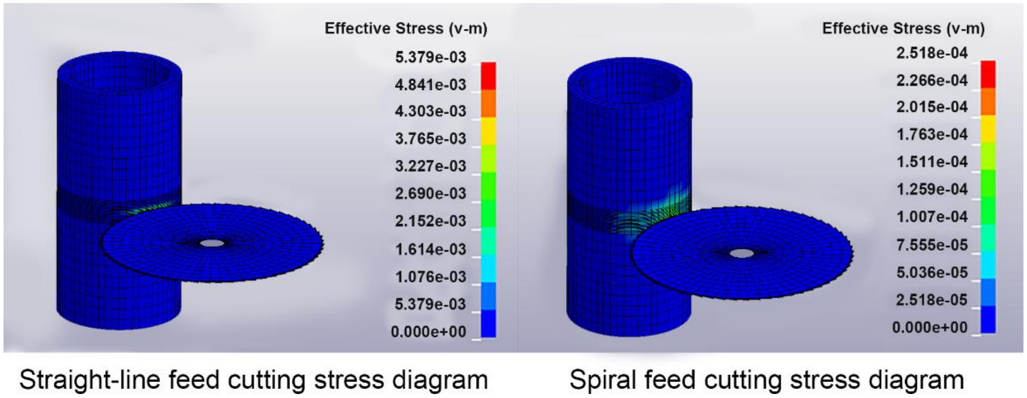


**Fig. 2.** Stress cloud diagram of cutting process

Because the splitting of bamboo occurs near the cutting position, six elements near the cutting position of the bamboo model (except for the two elements directly in contact with the saw blade) were taken for the tensile stress perpendicular to the crack surface, the stress is in the ZX direction in the ANSYS coordinate system. The position of the selected element is shown in Fig. 3.

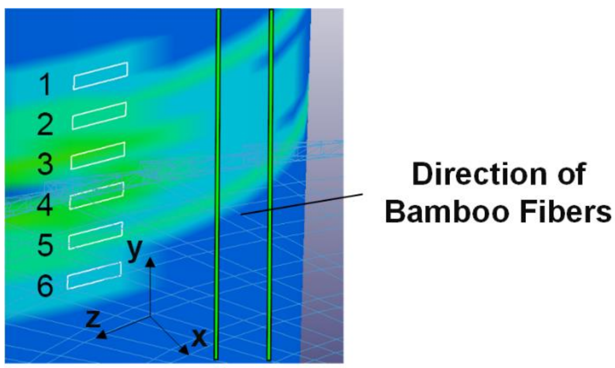


**Fig. 3.** Location map of the taken unit

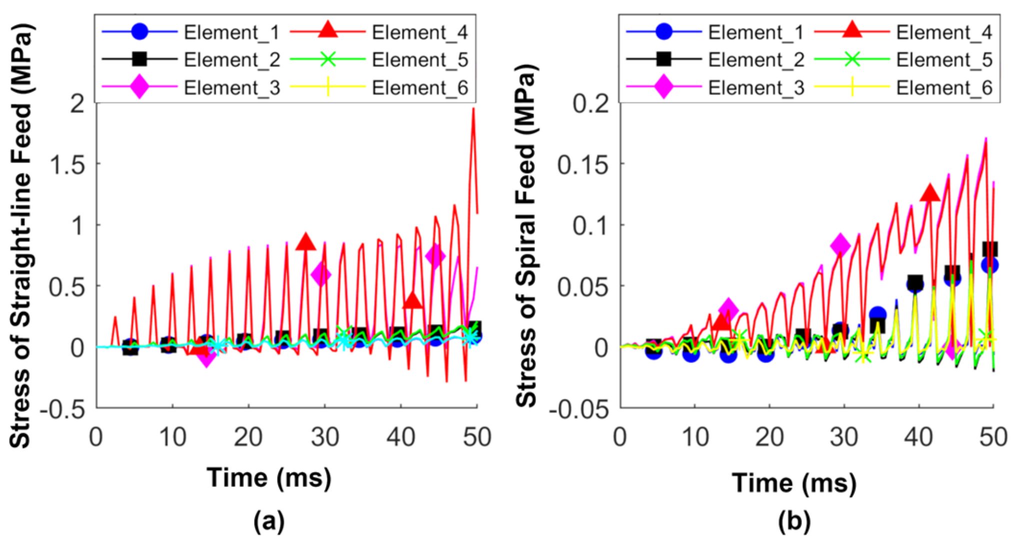


**Fig. 4.** Stress curve in ZX direction

The ZX-direction stress curves in the two cutting methods are shown in Fig. 4. The maximum ZX-direction stress of the linear feed cutting method was 1.96 MPa. At the same time, the maximum stress in the ZX direction of the spiral feed cutting method remained at 0.168 MPa. It can be seen that the ZX direction stress of the spiral feed cutting method is predicted to be much smaller than that of the linear feed cutting method, which means that this cutting method can effectively reduce the bamboo splitting during harvesting.

### Overall Scheme of Bamboo Cutting Mechanism

The scheme was designed based on the analysis of the cutting methods. In order to have uniform force and cutting efficiency, the cutting device uses four sets of saw blades. As shown in Fig. 5, the four sets of circular saw blades rotate at high speed and revolve around the center of the bamboo section. At the same time, the saw blade was fed radially toward the center of the bamboo for cutting, and the trajectory of the center of the saw blade was spiral centered on the center of the bamboo. Cutting in this way can greatly reduce bamboo splitting.

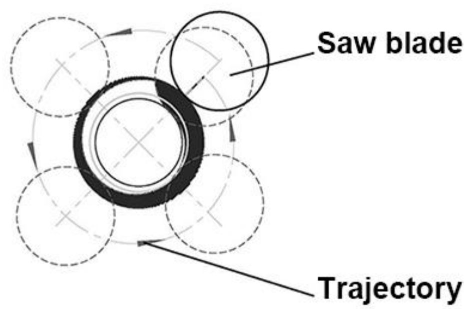


**Fig. 5.** Schematic diagram of cutting scheme

### Optimization of Cutting Parameters

After determining the cutting scheme, the cutting parameters were further optimized to reduce the cutting force during harvesting. As shown in Fig. 6(a), The outer diameter *D* of the selected saw blade is 90 mm, the inner hole diameter *d* is 22mm, and the number of teeth is 90.

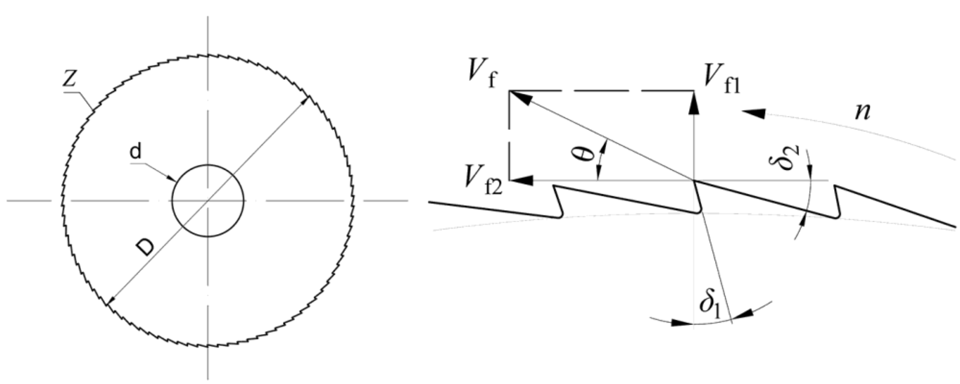


**Fig. 6.** Cutting parameters of saw blade cutting

As shown in Fig. 6(b), and the front angles $\delta_1$ and back angles $\delta_2$ of the tooth profile are both 15°. It can be seen from Fig. 6(b) that when the saw blade is in the cutting operation, there exists a rotating speed *n*, and the feed motion also includes radial speed $V_{f1}$ and tangential speed $V_{f2}$. The angle between the direction of rotation and the direction of feed is called movement encounter angle $\theta$.

The cutting power and cutting force at bamboo hollow with diameter of 100 mm were calculated. As shown in Fig. 7, taking the tooth tip as the research object, its relative motion trajectory was a cycloid AB, and CD was the cutting depth, *H* was saw road height.

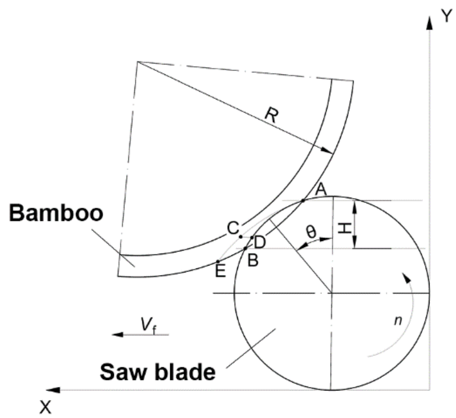


**Fig. 7.** Cutting power diagram of saw blade

Due to the particularity of bamboo, an empirical formula (Ma *et al.* 2006) was used to calculate the cutting power and cutting force during harvesting.

The unit initial cutting force *k* (N/mm$^2$) is,

$$k = 10 - 2.2b + 9.81 \times (0.07 - 0.001\delta)\theta \quad (3)$$

where *b* is the thickness of saw blade (mm), $\delta$ is cutting rake angle (°), and $\theta$ is work encounter angle (°).

The cutting amount per tooth $f_z$ (m/r) is expressed as Eqs. 5 and 6 (Zhu *et al.* 2020),

$$f_z = \frac{1000V_f}{Zn} \quad (4)$$

$$V_f = \sqrt{V_{f1}^2 + V_{f2}^2} \quad (5)$$

where $V_f$ is total feed rate (m/min), *Z* is number of saw blade teeth, and *n* is speed of saw blade (r/min).

Tool bluntness coefficient $C_p$ is given by,

$$C_p = 1 + \frac{0.2\Delta\gamma_n}{\gamma_{n0}} \quad (6)$$

$$\gamma_n = \frac{HnT}{10^6 \sin\theta} \quad (7)$$

where $\gamma_n$ is initial circle radius increment of cutting edge (μm), $\gamma_{n0}$ is circle radius increment of cutting edge (μm), *H* is saw road height (mm), and *T* is working hours (mm).

Specific cutting force $K$ (N/mm$^2$) is obtained from Eq. 8,

$$K = k + \frac{C_p p}{f_z} \tag{8}$$

where $p$ is tree species coefficient, for bamboo, $p$ = 0.15.

Cutting power $P_c$ (KW) and the cutting force $F_c$ (N) are obtained from Eqs. 9 and 10 (Zhu *et al.* 2020):

$$P_c = \frac{KbHV_f}{60 \times 1000} \tag{9}$$

$$F_c = \frac{6P_c}{\pi Dn} \times 10^7 \tag{10}$$

When the radial feed rate $V_{f1}$ = 0.1 m/min and the tangential feed rate $V_{f2}$ = 1.0 m/min, the relationship between cutting power, cutting force, and saw blade speed is shown in Fig. 8. It can be seen that when the speed is about $n$ = 1000 r/min, the cutting force has a minimum value. At the same time, the cutting power increased with increasing speed.

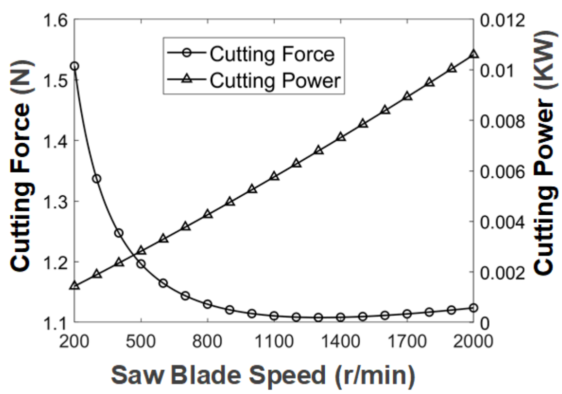


**Fig. 8.** Effect of saw blade speed on cutting force and power

When the saw blade speed was $n$ = 1000 r/min, the axial feed rate was $V_{f2}$ = 1.0 m/min, the relationship between the cutting power, force, and the radial feed rate was as shown in Fig. 9(a).

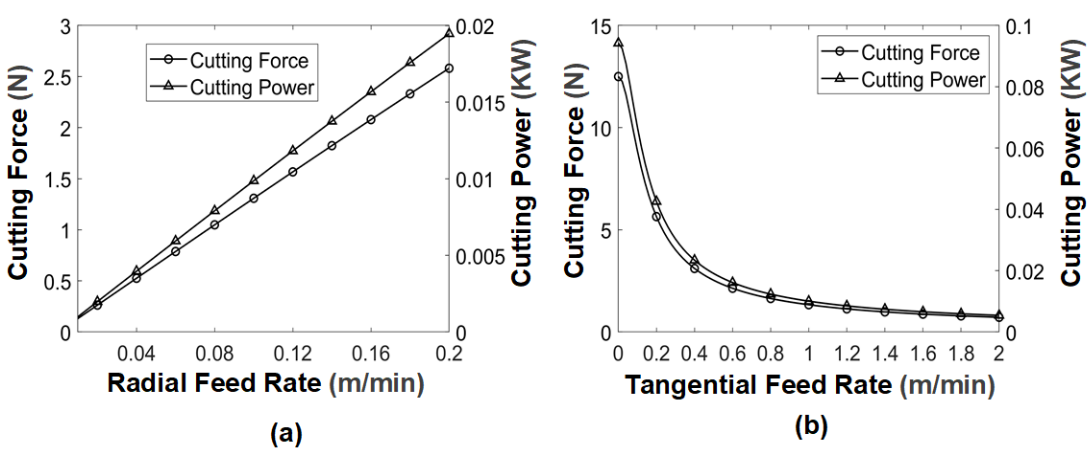


**Fig. 9.** Effect of feed rate on cutting force and power

Both cutting power and cutting force increased with the increase of radial feed speed. When the saw blade speed was $n$ = 1000 r/min, the axial feed rate was $V_{f1}$ = 0.1 m/min, the relationship between the cutting power, force, and the tangential feed rate is shown in Fig. 9(b). Both cutting power and cutting force increased with decreasing of tangential feed speed.

From the above calculation and analysis, to reduce the cutting force and power consumption, the saw blade speed was set to $n$ = 1000 $r$/min. While considering the cutting efficiency, the radial feed speed cannot be too small, the radial feed rate was set to $V_{f1}$ = 0.2 m/min and the tangential feed rate was set to $V_{f2}$ = 1.0 m/min under comprehensive consideration.

## Optimization of Cutting Parameters

Based on the above calculations, the bamboo cutting mechanism was specifically designed. Its overall structure is shown in Fig. 10. It consists of hydraulic cylinder, link mechanism, cutting mechanical claw frame, and saw blade holder. The graphic position denotes the cutting position, the two hydraulic cylinders drive the mechanical claws to close through the linkage mechanism and cut the bamboo.

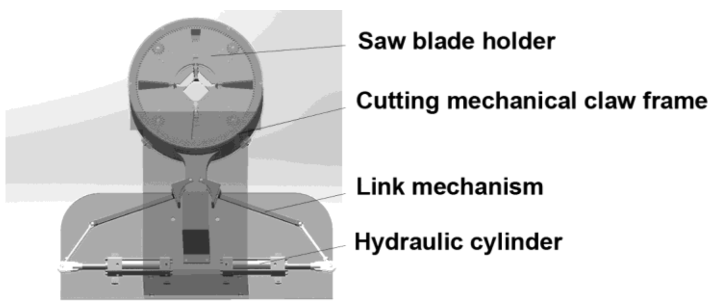


**Fig. 10.** Overall structure of the bamboo cutting mechanism

The gear on the saw blade holder and the gear ring on the cutting mechanical claw frame cooperate when cutting, so that the saw blade holder can revolve on the closed mechanical claw frame. At the same time, radial feed movement of saw blade was mounted through internal gear and spiral transmission. The main transmission route of the saw blade holder is shown in Fig. 11(a). Its specific structure is shown in Fig. 11(b).

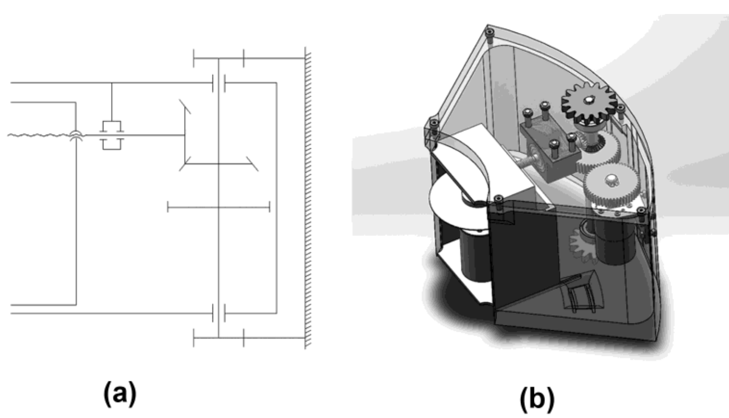


**Fig. 11.** Transmission route (a) and specific structure (b) of saw blade holder

The motion of a single saw blade was analyzed through the motion module of the SolidWorks software. The trajectory can be obtained as shown in Fig. 12(a). The theoretically designed spiral trajectory equation is Eq. 11:

$$\begin{cases} x = (50 - \theta / 18)\cos(40t) \\ y = (50 - \theta / 18)\sin(40t) \end{cases} \tag{11}$$

The trajectory curve data obtained by the simulation was derived theoretically and compared with the theoretical spiral trajectory curve. As shown in Fig. 12(b), it can be seen that the simulation curve and the theoretical curve completely overlap, and the designed felling mechanism can complete the predetermined spiral feed movement.

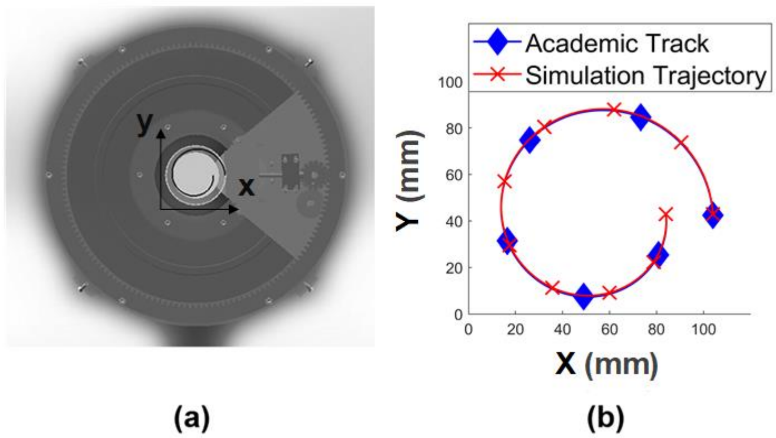


**Fig. 12.** The trajectory diagram of saw blade movement

## CONCLUSIONS

1. Looking at the splitting problem of bamboo cutting, the cutting process of bamboo was analyzed and simulated based on the principle of crack propagation, and the advantages of the spiral feed cutting method compared with the linear feed cutting method were verified.
2. Based on the analysis results, a symmetrically distributed multi-group saw blade spiral feed cutting scheme was proposed, and the specific design parameters of the cutting plan were optimized, appropriate saw blade speed and feed speed in two directions were determined.
3. Relying on the plan and optimized parameters, the specific structure of the bamboo cutting mechanism was designed, and the model of the mechanism was established, and its kinematic characteristics were analyzed to verify the feasibility of the proposed mechanism.

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