Design and test of the crank slider mechanism feeding type rubber rotary cutting machine

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Received: 20 November 2019 / Accepted: 7 April 2020 / Published online: 16 April 2020
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Abstract

Aiming at the problems such as low processing efficiency and high labor intensity when the rubber block was processed, a new type of crank slider mechanism feeding style rubber rotary cutting machine was designed with the help of computer. Starting with the two major processing steps of pushing and cutting the rubber block, an offset crank slider mechanism was used to push the rubber block in order to improve the processing efficiency of the rubber block. The V-belt was driven by the motor to rotate the circular saw blade, and the ball screw drove the rubber cutting table to make the rubber block perform reciprocating linear motion. The synthesis of the above two motions could achieve efficient cutting of the rubber block. Taking the needs of the rubber block cutting process into account, the flat belt width of the transmission rubber block was designed to be 355 mm, so that the machine had a good adaptability to rubber blocks. The modal simulation analysis determined that the optimal thickness of the circular saw blade was 3 mm and the optimal diameter of the circular saw blade was 500 mm. And the static finite element simulation analysis results also showed that the circular saw blade with this set of parameters had good strength and stiffness. After the orthogonal test was conducted on the prototype of crank slider mechanism feeding style rubber rotary cutting machine, the test results showed that the machine could cut 15 rubber blocks averagely per minute and each test produced less than 10 g rubber residue. In a word, the designed machine not only improved the cutting efficiency, but also met the demand for green and efficient processing of the modern agricultural products.

Keywords Rubber rotary cutting machine · Finite element modeling · Simulation analysis · Orthogonal test

1 Introduction

Rubber tree is a typical tropical characteristic plant native to tropical forests of Amazonia in South America, and the natural rubber it produces is an important strategic material indispensable to modern industry. Rubber trees have been introduced into China for more than one hundred years. The main rubber planting areas are located in Danzhou, Qiongzong and Wanning and other counties of Hainan province of China. As the most important rubber production base in China, Hainan produces about 2/3 of the country's total [1, 2], and more than 1 million people are engaged in

rubber related industries directly or indirectly, which has huge potential for development. At present, the cultivation of rubber trees in Hainan has become large-scale, and the rubber processing, transportation, and sales industries that have developed along with them have become the pillar industries in Hainan Province [3]. There are dozens of rubber processing companies in Hainan Province, but only a few companies have a certain degree of specialized rubber comprehensive processing capacity. However, the work on cutting rubber is still in its infancy. The work of cutting rubber blocks is labor-intensive, inefficient, time-consuming and labor-intensive, and it has certain safety risks.

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At present, there are some research results on the design and analysis of rubber block cutters. In literature [4], a three-dimensional geometric model of a vertical rubber cutter was created using CAD software and imported into the CAE software for finite element modeling. Then the modal finite element analysis of the cutting machine was carried out, and the first four order natural frequency and vibration mode of the cutting machine were obtained. Literature [5] developed a new type of pneumatic cutter, which is simple in structure and uses compressed air as the driving force. Compared with traditional hydraulic cutters, the oil leaking can be avoided, and the working environment is optimized on the premise of improving the quality of the rubber cutting. The effect of cutting speed and angle on the cutting performance of natural rubber is studied in literature [6]. The results show that high speed or high angle cutting eliminates the crack defects on the machined surface and reduces the defects at the entrance edge of the workpiece, and provides a reference for the high quality work of the rubber rotary cutting machine. In order to obtain the mechanism of rubber cutting, literature [7] correctly evaluate the influence of cutting speed and cutting edge sharpness on cutting resistance, and a cutting test device was designed. Through mechanical analysis of the cutting process of rubber, the theoretical basis is provided for the development of high performance cutting machine. However, the above studies mainly aim at the process of cutting the rubber rotary cutting machine. The feeding of the rubber block mainly depends on manual operation, and the degree of automation is low, which is not conducive to improving the cutting efficiency and the safety of the rubber cutting work.

In order to solve the above problems, this paper designs a crank slider mechanism feeding type rubber rotary cutting machine for crank slider mechanism. According to the requirements of the processing technology of the rubber block, the structural parameters of the pushing device are determined and the push time is reduced. By means of finite element modal analysis and static analysis, suitable circular saw blade structure is selected to reduce residue produced during cutting of rubber blocks. Finally, the orthogonal test is carried out on the prototype to determine the best parameter combination to improve the performance of the machine and ensure that the obtained rubber block meets the technological requirements.

2 Overall structure and working principle

2.1 Whole structure

The structure of the crank slider mechanism feeding type rubber rotary cutting machine designed in this paper, as

shown in Fig. 1, mainly includes the pushing device, the conveying device, the rubber cutting device, the rubber block positioning device, the collection box, the automatic control system and so on. The pushing device of the machine adopts an offset crank slider mechanism to push the rubber block, and the V belt drives the circular saw blade to rotate. The rubber block performs reciprocating linear motion under the drive of the ball screw, thereby realizing the cutting of different types of rubber blocks. The automatic control system coordinates and controls the pushing, conveying and cutting process of the rubber block. Among them, the offset crank slider mechanism has a snapback feature, which improves the speed of the push rubber block. The V-belt drive structure is compact, the transmission is smooth, and the transmission efficiency is high. The tooth shape of the circular saw blade is relatively sharp, and the rubber residue generated after cutting is relatively less, which improves the quality of the cutting rubber and facilitates the subsequent processing of rubber products.

2.2 Working principle

During the working process, the rubber block is placed on the machine's rubber stand, the slider of the crank slider mechanism (or the push block) pushes the rubber block to the conveyor belt, the conveyor belt drives the rubber block movement, and the rubber block is transferred to the gum cutting table. The rubber cutting table is driven to the saw blade under the ball screw drive, and then the rubber table is cut under the rotation of the saw blade. The rubber block is cut in half, which completes the automatic cutting of a rubber block. When the slider is returned, the next block is put on the deposit table. The slider is pushed

Fig. 1 Rubber rotary cutting machine. 1. Automatic control system 2. Pushing block 3. Storage tray 4. Conveyor belt 5. Servo motor. 6. Ball screw 7. Rubber cutting table 8. Rubber block positioning device 9. Circular saw blade 10. Collection box

to the conveyor belt and then the rubber block is transferred to the rubber cutting table. Therefore, the continuous feeding of the rubber block can be guaranteed.

During the reciprocating movement of cutting rubber, the rubber block is pushed toward the rapidly rotating circular saw blade. Since there is a debris collecting box under the saw blade, when the circular saw blade cuts the rubber block into two parts, the rubber residue falls from the cut into the collection box, which avoid the work environment pollution caused by residue. At the same time, when a rubber block cutting is completed, the rubber cutting table driven by the ball screw reverse reset, and the two blocks obtained by cutting are removed quickly. The next rubber block on the conveyor belt goes into the rubber cutting table, and then the new cutting process is repeated again. Thus, the continuity of the cutting work of the rubber block is realized by such a reciprocating cycle. Among them, the push block and the circular saw blade are all made of stainless steel to ensure that the entire process does not contaminate the rubber block.

Fig. 2 Pushing device's schematic diagram. 1. Motor, 2. Belt drive mechanism, 3. Reducer, 4. Crank, 5. Connecting rod, 6. Push block

3 Pushing device design and analysis

The schematic diagram of the structure of the pushing device is shown in Fig. 2. The motor drives the crank to rotate at a constant speed through a belt transmission mechanism and a decelerator, and the crank drives the slider to reciprocate through the connecting rod. Because the offset crank slider mechanism has a snapback feature, the slider accelerates when the rubber block is pushed, and slams back in the idle process, thereby improving the efficiency of pushing the rubber block.

3.1 The establishment of pushing device's mathematical model

The coordinate system of the offset slider crank mechanism is established with the center of the end of the reducer output shaft as the coordinate origin, as shown in Fig. 3.

In Fig. 3, r_2 and r_3 are the length of crank and connecting rod. e is the offset. θ_1 is the angular displacement of the crank, θ_2 is the angular displacement of the connecting rod, r_1 is the displacement of the slider, and the position motion equation of the offset crank slider mechanism [8] is established:

$$\vec{r}_2 + \vec{r}_3 = \vec{r}_1 + \vec{e} \quad (1)$$

Decomposing $\vec{r}_1$, $\vec{r}_2$, $\vec{r}_3$ and $\vec{e}$ on x and y coordinate axes, we can get:

Fig. 3 Offset crank slider mechanism diagram

$$r_2 \cos \theta_1 + r_3 \cos \theta_2 = r_1 \quad (2)$$

$$r_2 \sin \theta_1 + r_3 \sin \theta_2 = e \quad (3)$$

Equations (2) and (3) can be derived for time to obtain the velocity equation:

$$-r_2 \omega_1 \sin \theta_1 = v_1 + r_3 \omega_2 \sin \theta_2 \quad (4)$$

$$-r_2 \omega_1 \cos \theta_1 = r_3 \omega_2 \cos \theta_2 \quad (5)$$

where ω_1 is the angular velocity of the crank, ω_2 is the angular velocity of the connecting rod, and v_1 is the linear velocity of the slider relative to the ground.

3.2 Kinematic analysis on pushing device

In the actual production process of the rubber block processing plant, the average time for cutting a rubber block is in the range of 5 to 8 s. In order to increase the production efficiency, it is advisable to control the time for cutting one rubber block within 4 s. In order to smoothly push the rubber block onto the cutting table, a flat belt conveying device is arranged between the pushing device and the cutting device. The length of the standard rubber block is generally 680 mm and the width is generally 340 mm. According to the "size and tolerance of GB/T 11358-1999 belt drive belt and belt wheel", the width of the conveyor belt is selected as 355 mm, and the belt length is selected as 5000 mm, so that the machine can adapt to the processing of different sizes of rubber blocks.

In this machine, the moving stroke of the conveyor belt is 2500 mm. In order to make the machine cut a rubber block within 4 s, the speed of the conveyor belt should be at least 0.625 m/s. In order to ensure the smoothness of the transmission, the speed of the pushing block should also be 0.625 m/s. According to the requirements of the rubber block cutting process, the coefficient of the ratio of the stroke ratio of the offset crank slider mechanism is taken as 1.55, and the calculation is performed according to the relationship among various components. The crank length r_2 is 190 mm, the connecting rod length r_3 is 325 mm, and the offset distance e is 105 mm. The kinematics analysis of the offset crank-slider mechanism is performed, and the crank angular velocity is obtained as $\omega_1 = 1.57$ rad/s. The converted output speed of the reducer is $n = 15$ r/min. The initial angular displacement of the crank angle θ_1 is set to 0. This determines the main technical parameters of the machine crank slider mechanism shown in Table 1.

The parameters in Table 1 were brought into Eqs. (2) to (5) for solving with the help of computer. The results obtained are shown in Table 2.

4 Cutting device and its transmission method

The structure of the rubber cutting device of the machine is shown in Fig. 4. The motor drives the circular saw blade to rotate through the V-belt drive mechanism to cut the rubber block. The material of the circular saw blade is martensitic stainless steel. The maximum speed

Table 2 Mathematical model's solution results

Parameter	θ_2/rad	θ_2	r_1/mm	$\omega_2/(\text{rad/s})$	$v_{1/}/(\text{m/s})$
Value	0.33	18.85°	496.57	0.97	0.625

of the circular saw blade is 2950 r/min, which can meet the requirements for cutting various rubber blocks.

The rubber cutting device adopts a V-belt drive mechanism, the V-belt model is Z-type, the transmission ratio i is 1.4, and the material of the pulley is HT150. The design is a solid structure, as shown in Fig. 5, and the pulley width is 25 mm. When the three-phase asynchronous motor drives the belt wheel and the transmission system has not worked, the initial pulling force of the V belt is F_0 , and the pressure of the shaft is Q . The initial pull of the V band is 82.19 N with the formula (6) and (7), and the pressure with the axis is 328.75 N.

$$F_0 = 500 \times P_c \left(\frac{2.5 - K_\alpha}{zvK_\alpha} \right) + qv^2 \quad (6)$$

$$Q = 2F_0z \sin \frac{\alpha_1}{2} \quad (7)$$

where P —calculated power, $P_c = 2.64$ Kw, K_α —wrap angle correction factor, $K_\alpha = 0.92$, α_1 —roller wrap angle, $\alpha = 150^\circ$, z —V band number, $z = 2$, v —speed, $v = 13.38$ m/s.

q —mass with unit length, $q = 0.06$ kg/m.

Fig. 4 Rubber cutting device's schematic diagram. 1. Three-phase asynchronous motor 2. V-belt drive mechanism 3. Servo motor. 4. Ball screw 5. Cutting Table 6. Saw blade

Table 1 Known parameters of crank slider mechanism

Parameter	r_2/mm	r_3/mm	e/mm	$\omega/(\text{rad/s})$	θ_1/rad
Value	190	325	105	1.57	0

Fig. 5 Belt wheel's structure

5 Finite element simulation analysis and optimization of circular saw

During the cutting process of the rubber block, the circular saw blade must maintain the sharpness of the cutting for a long time under the condition of rapid cutting and impact loading, which has certain requirements on the tooth profile, thickness and diameter of the saw blade. Taking into account the cutting rubber block can not produce too much rubber residue, the use of zigzag saw blade. If the thickness of the saw blade is too small or the diameter is too large, the saw blade may vibrate during operation, which may affect the cutting effect. If the thickness is too large, too much debris may be generated when cutting the rubber block. In order to solve this problem, the ANSYS software is used to make modal analysis of the saw blade, select the suitable diameter and thickness, and carry out static analysis of the saw blade to ensure that the blade has enough strength and stiffness.

5.1 Force analysis of circular saw blades

During the process of cutting the rubber block by the circular saw blade, the saw blade is subjected to the cutting force F of the saw block in the sawing arc zone, and the component force is the radial force F_n and the tangential force F_t of the circular saw blade, as shown in Fig. 6. When the circular saw blade cuts the rubber block, the relationship between the saw tooth number and the cutting depth is as follows:

$$Z = \frac{K}{P} a_r \cos \left(1 - \frac{a_p}{R} \right) \quad (8)$$

Fig. 6 Cutting force diagram of circular saw blade

In the formula, Z —the number of saw teeth involved in cutting, a_p —cutting depth, R —saw blade radius, P —tooth pitch.

When the rubber block is cut, the radial force F_n of the circular saw blade is generated by the extrusion of the saw blade and the rubber block. The tangential force F_t is generated by the friction between the saw blade and the rubber block. As is known from formula (8), the greater the depth of cut, the more teeth are involved in cutting.

During the cutting of the rubber block by the saw blade, the radial force F_n and the tangential force F_t are considered. The cutting force of the saw blade can be obtained from the formula for the power axis torque of the saw blade:

$$\begin{cases} N = \frac{N_1 + N_2 + N_3 + N_4}{\eta_{total}} - N_{\Delta E} \\ M_t = 9550 \times \frac{N}{n} \\ M_t = F_t \times \frac{D}{2} \\ F_t = 19100 \times \frac{N}{D \cdot n} \end{cases} \quad (9)$$

where: N —average sawing power, Kw, n —shaft speed, r/min, M_t —saw shaft torque, Nm, D —saw blade diameter, mm, N_1 —average power used for sawing in the sawing process, Kw, N_2 —power required to bend the workpiece, Kw, N_3 —clip Saw Power, Kw, N_4 —no-load power, Kw.

5.2 Establishment of finite element model of circular saw blade

The three-dimensional model of the circular saw blade was established by Pro/Engineer software in computer, and the finite element modeling was introduced into the ANSYS software [9–12] in computer. In order to make the finite element model conform to the actual situation, the solid element SILID185 was used to mesh the circular saw blade.

The rotational speed of the circular saw blade is 2950r/min, and the parameters of the saw blade are as follows: the modulus of elasticity $E = 2.1 \times 10^5$ MPa, the density $\rho = 7930$ kg/m³, the Poisson's ratio $\mu = 0.3$. The finite element model of the circular saw blade is shown in Fig. 7.

5.3 Modal simulation analysis of circular saw blades

In the production process of the factory, the thickness and diameter of the saw blade will affect the rubber residue generated during cutting. In this paper, modal analysis is performed for saw blades of different diameters and thicknesses. The simulation conditions are set respectively as follow, that is the saw blade modes with fixed thickness

Fig. 7 Finite element model of circular saw blade

of 3 mm and diameters of 300 mm, 400 mm, 500 mm and 600 mm, the saw blade modes with fixed thickness 4 mm and diameters of 300 mm, 400 mm, 500 mm and 600 mm, and the saw blade modes with fixed thickness 5 mm and diameters of 300 mm, 400 mm, 500 mm and 600 mm. After completing the above analysis in modal simulation module of ANSYS workbench software, the first five natural frequencies of the circular saw blades with different diameters and thicknesses are shown in Table 3. The modal analysis results are shown in Figs. 8 and 9. The results show that the natural frequency of the circular saw blade increases with the increase of saw blade thickness, and decreases with the increase of saw blade diameter.

According to the dynamic theory, the relationship between the rotational speed and the angular speed of the saw blade during the rotation is as follows

$$\omega = 2\pi n/60 \quad (10)$$

n —rotational speed of saw blade, ω —angular speed of saw blade.

Fig. 8 The influence of diameter on the natural frequency of the circular saw blade

Table 3 Circular saw blade's first 5 order natural frequency

Thickness / mm	Diamete/mm	Natural frequency/Hz				
		1	2	3	4	5
3	300	140.18	141.21	169.11	210.67	214.46
	400	85.91	88.48	105.56	127.31	128.61
	500	58.91	59.78	71.52	85.52	88.63
	600	45.37	45.84	55.39	62.92	66.96
4	300	179.43	180.81	215.51	273.13	276.19
	400	105.27	106.67	127.51	158.03	160.74
	500	73.88	74.13	88.97	108.35	109.15
	600	53.89	54.43	65.67	78.36	80.13
5	300	216.86	217.13	261.3	336.79	339.97
	400	126.51	126.74	152.22	193.69	193.98
	500	85.24	85.51	102.7	127.24	129.09
	600	61.41	62.44	74.55	90.71	92.28

Fig. 9 The influence of thickness on the natural frequency of the circular saw blade. **a** The first order modal. **b** The second order modal. **c** The third order modal. **d** The fourth order modal. **e** The fifth order modal

The rotation period of saw blade is as follows

$$T = 2\pi/\omega \quad (11)$$

T —rotation period.

Then the rotation frequency of the saw blade is as follows

$$f = 1/T \quad (12)$$

f —vibration frequency.

According to the above equations, the rotation frequency can be obtained.

$$f = n/60 \quad (13)$$

In order to avoid resonance during the rotation of the saw blade, the rotation frequency cannot be equal to or too close to the natural frequency of each order of the saw blade [13–16].

The maximum speed of the circular saw blade is 2950 r/min, and it is calculated from Eq. (13) that the excitation frequency is 49.17 Hz, in order to avoid the resonance phenomenon of the saw blade and the frequency should be avoided. According to the processing requirements of the block, the excitation frequency should be 15% lower than the first natural frequency of the circular saw blade, and the first natural frequency of the circular saw blade is obtained. And the rate is 57.84 Hz. The height of the rubber block is approximately 200 mm, which can be 190~210 mm. In order to cut the rubber block completely, the radius of the saw blade should be greater than 210 mm, which means the diameter of the saw blade should be greater than 420 mm. Compared with the results shown in Table 3, it is more suitable to choose a circular saw blade with a thickness of 3 mm and a diameter of 500 mm, which can not only ensure good dynamic characteristics, but also make the machine realize the structure light weight. The mode shape of the first five order natural

frequencies of the circular saw blade with above parameters is shown in Fig. 10. It can be seen from Fig. 10 that the main vibration deformation of the saw blade occurs on the sawing teeth, and the maximum deformation of each order modal is much smaller than the size of the circular saw blade.

5.4 Static simulation analysis of circular saw blades

According to the formula (9), when the sawing depth of the circular saw blade is 20 mm, the two force of the cutting back force of the saw blade is the radial force $F_n = 36.78$ N and the tangent force $F_t = 160.24$ N. Then there are two saw teeth on the saw blade, and the pressure of the two saw teeth is regarded as all the pressure, and the force area is the bottom and the side of the cutter teeth. The saw blade only rotates in an axial direction during sawing. It is fixed in other degrees of freedom, and the rotation of the motor is driven by the motor. In the ideal condition, it is also considered to be constrained. Therefore, the entire circle area of the inner hole is fully constrained.

In the ANSYS software, according to the simulation constraints and loading conditions described above, the static analysis is performed after the circular saw blades are set. The results of the deformation distribution and stress distribution of the circular saw blades are shown in Figs. 11 and 12, respectively.

Analysis of Fig. 11 shows that the main deformation of the saw blade occurs on the right side of the sawing teeth. The deformation is mainly caused by the rapid rotation of the saw blade. The maximum deformation is 15.017×10^{-3} mm, which is much smaller than the size of the circular saw blade, and it is negligible. On the same side of the saw tooth, due to the effect of the rubber block on the cutting reaction, the deformation is relatively small.

Figure 12 shows that the stress of the saw blade is mainly concentrated around the hole. The maximum stress is 22.305 MPa, and the stress at the sawing tooth and the tooth groove is smaller, which is much smaller than the yield strength of the material 205 Mpa, so the strength and rigidity of saw blades meet the requirements of work.

5.5 Discussions of design result

In order to solve the problems of low processing efficiency and high labor intensity of the current rubber block, a new kind of the crank slider mechanism feeding type rubber rotary cutting machine was designed. Based on the mathematical model of the offset crank slider mechanism and considering the requirement of the rubber cutting process, the conveyor belt width of the conveyor block is designed

Fig. 10 The mode shape of the first five order natural frequencies

to be 355 mm, so that the machine has good adaptability to the different sizes of the rubber block.

In order to avoid the phenomenon of resonance when the saw blade of the feed mechanism of the slider and slider mechanism is fed, finite element modal analysis

is performed on the saw blade to determine that the thickness of the saw blade is 3 mm, and the diameter is 500 mm. The static finite element analysis shows that the structure of the saw blade with this group of parameters also has good strength and stiffness.

Fig. 11 Circular saw blade's deformation distribution

Fig. 12 Stress distribution of circular saw blade

6 Experimental verification of saw blade modal finite element analysis

6.1 Experimental purpose

In order to verify the correctness of the finite element modal simulation analysis of the saw blade, a modal experiment was performed on the saw blade. The purpose of the modal experiment is to obtain the first five order natural frequencies.

6.2 Experimental equipment

The experimental equipment includes a force hammer, a force sensor (on the top of hammer), an acceleration sensor, a LMS test system and a computer (including a modal analysis software). The sensor parameters used in the experiment are as follows: the sensitivity of the force sensor is 0.23 mv /N, and the sensitivity of the

Fig. 13 Experimental equipment

Fig. 14 Modal experimental principle

acceleration sensor in the X-axis, Y-axis, and Z-axis directions is 100.6 mv/g, 97.2 mv/g, and 97.2 mv/g respectively. The experimental equipment is shown in Fig. 13.

6.3 Experimental principle and process

The modal experimental principle for saw blade is shown in Fig. 14, and the distribution of the modal test points is as shown in the Fig. 15. The modal experiment on saw blade was carried out by using a method of single point excitation and multi-point picking, whose main process is as follows.

(I) The modal test points on the saw blade were selected according to Fig. 15. The modal experimental equipment was set in accordance with the experimental principle schematic shown in Fig. 14.

(II) The excitation force was applied to the saw blade through using hammer, and the acceleration sensors were fixed on the modal test points on saw blade.

(III) The force sensor collected the excitation force; the force signal was transmitted to the LMS test system; the acceleration sensor collected the acceleration response signal caused by the excitation force and transmitted it to the LMS test system.

Fig. 15 Test points

(IV) After setting the related parameters in modal analysis software, the signals collected by the sensors were transmitted to the computer through the LMS test system, and then the frequency analysis of saw blade was conducted by using modal analysis software in computer.

(V) Based on the saw blade's frequency analysis results, the first five order natural frequencies of saw blade were identified and obtained.

6.4 Experimental results and analysis

After conducting the modal experiment of the saw blade, the experimental results of the natural frequencies of saw blade compared with the simulation results were obtained as shown in Table 4. Table 4 shows that the relative error between the simulation and the experimental values of the first five order natural frequencies of the saw blade is rather small, which verifies the finite element stimulation modal analysis method of the saw blade is reasonable and feasible.

7 Rubber cutting test and result analysis

7.1 Test purpose

In order to test the working performance of the prototype of the crank slider mechanism feeding type rubber rotary cutting machine, the influence of the structural parameters of the saw blade on the residue of the cutting rubber block was investigated, and the optimum structure size of the saw blade was determined. The prototype was subjected to a rubber block cutting test.

Table 4 Comparison of experiment and simulation

Modal orders	Natural frequencies /Hz		Relative error (%)
	Simulation value	Experimental value	
The first order	58.91	57.88	− 1.75
The second order	59.78	60.96	1.97
The third order	71.52	70.03	− 2.08
The fourth order	85.52	87.45	2.26
The fifth order	88.63	90.92	2.59

7.2 Test Equipment and conditions

The speed reducer of the prototype pusher is a turbine worm reducer. The efficiency is between 0.65 and 0.7, and the output speed n is 15 r/min. According to the requirements of the factory, the required torque of the drive equipment T is 930 Nm and $\eta = 0.7$. According to formula (14), the maximum power required by the calculation is 2.09 Kw. Therefore, a Y2-90L-2 three-phase asynchronous motor with a rated power of 2.2 Kw is selected.

$$P = \frac{T * n}{9550\eta} \quad (14)$$

AA rubber block made of natural rubber produced from a high-quality rubber tree in Dangzhou, Hainan, which was 12 years old, was used as a test sample, as shown in Fig. 16. Each rubber block has a length of 680 mm and a width of 340 mm. The height of the rubber block is about 200 mm, and the mass of each rubber block is about 16.5 kg. The rubber block was tested within 10 days after purchase. The rubber residue weighing apparatus uses a tray balance with an accuracy of 0.1 g.

7.3 Test program

Since the crank slider mechanism feeding type rubber rotary cutting machine will produce a certain amount of rubber residue when the rubber block is cut, the residue will fall into the collection box below the machine. When the gel cutting test is completed, the residue in the collection box is collected and weighed, and the mass is the amount of residue. In the process of rubber block cutting test, different factors have different effects on the amount of residue. According to the structure of this machine, the orthogonal test [17–20] is carried out with 3 factors: the height of the rubber block, the thickness of the saw blade and the diameter of the saw blade. Each factor has 3 levels. In order to reduce the number of experiments,

Fig. 16 Tested rubber block samples

Table 5 Orthogonal test's factor levels

Level Factor	1	2	3
rubber block height(A)/mm	190	200	210
saw blade thickness(B)/mm	5	4	3
saw blade diameter(C)/mm	600	500	400

the standard orthogonal table is selected and 30 blocks are treated at each test. The test factors are as shown in Table 5.

7.4 Test results and variance analysis

According to the orthogonal test design scheme, nine cutting tests were performed, three factors occupied three columns, and one blank column was reserved as an error. The test plan and results are shown in Table 6. After statistics and analysis during the test, the machine can cut 15 rubber blocks per minute.

In order to detect the error of the test and test the significance of the test factors, the variance analysis of the above-mentioned orthogonal test results was performed using SPSS software in computer. The analysis results showed that the significance values of the three factors A, B and C are $P(A) = 0.002$, $P(B) = 0.013$, and $P(C) = 0.043$, and they are all less than 0.05, which shows that A, B, and C have influences on the residue of the rubber block, in which the two factors, the height of the rubber block and the thickness of the saw blade, have a significant effect on the residue, while the diameter of the saw blade has little effect. According to $P(A) < P(B) < P(C)$, the primary and secondary relationships of the three factors could be described as, rubber block height is the best, next is saw blade thickness, saw blade diameter is

Table 6 Orthogonal test and its result

Test number	A	B	C	D (blank column)	Rubber residue/g
1	1	1	1	1	3.92
2	1	2	2	2	3.78
3	1	3	3	3	3.75
4	2	1	2	3	4.37
5	2	2	3	1	4.29
6	2	3	1	2	4.23
7	3	1	3	2	4.63
8	3	2	1	3	4.51
9	3	3	2	1	4.41

Fig. 17 The results of test

the worst between them. The higher the height of the rubber block is, and the larger the volume of the rubber block is, so the more residue generated from cutting the rubber block is. Therefore, the effect of the height of the rubber block have a significant effect on the residue. According to the orthogonal test results, the test results are shown in Fig. 17.

Figure 17 shows that the preferred combination of the three factors is A1B3C2. At this time, the amount of rubber residue produced by the work is the minimum, that is, the height of the rubber block is 190 mm, the thickness of the saw blade is 3 mm, and the diameter of the saw blade is 500 mm. According to the modal analysis results, the preferred dynamic combination of circular saw blades has good dynamic characteristics. Therefore, the machine adopts the structural parameters of saw blades to meet the optimum combination. The amount of residue produced by cutting rubber blocks is less, and the dynamic characteristics is good.

The orthogonal test is carried out on the prototype, and the results show that the structural parameters

determined by modal analysis are the best structural parameters.

The cutting test was performed on the prototype of the crank slider mechanism feeding type rubber rotary cutting machine, and the cutting process was performed smoothly. The test results showed that the machine can cut 15 rubber blocks per minute on average. The amount of rubber residue generated in each test is less than 10 g, and the obtained rubber blocks meet the process requirements. It is in line with the green and efficient addition of the modern rubber industry, which is beneficial to improve the economic benefits of rubber processing enterprises.

8 Conclusions

In order to avoid the resonance of the saw blade during the work process, this paper proposes to use the modal finite element analysis and comparison method to determine the thickness and diameter of the saw blade in the simulation design environment, and the finite element static analysis method is used to verify the correctness of the optimized results. The above method can avoid the waste of materials brought by the traditional trial design method, and reduces the prototype trial production time, which is beneficial to improving the design efficiency.

In this paper, the rubber block pushing mechanism is designed as an offset crank slider mechanism, and the mathematical model of the mechanism is established by using the kinematic principle to solve the structural parameters of the mechanism according to the design requirements. The rubber block pushing mechanism has a quick return characteristic, so the slider accelerates when pushing the rubber block, and returns quickly when idling, thereby improving the efficiency of pushing the rubber block.

The mechanical theory and knowledge of mechanism kinematics is used to design a new rubber rotary cutting machine in this paper, and the finite element simulation technology is applied to calculate and solve design parameters. The feasibility of the design results is verified by modal experiment and actual cutting tests. To sum up, the integrated method of theoretical research, simulation analysis and experimental verification is adopted to conduct mechanical design research in this paper, which also provides a reference method for the research of other engineering design problems.

Acknowledgements This study was funded by the China Scholarship Council (Grant No. 201907565009) and the Open Fund Project of Jiangsu Key Laboratory of Precision and Micro-Manufacturing Technology.

Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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