

Construction and finite element simulation of the saw type gin stand using fractal theory

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Abstract

The process of cotton ginning was simulated by the finite element method in order to improve and optimize the efficiency of the process. Based on the fractal theory, a new cotton model was established by observing the morphological structure of cotton: the fractal cotton model with cotton seed. Considering the existence of seeds in actual cotton, the model assumes that the cotton fiber bundles are distributed in a fractal structure and the section is simplified as a circle. The finite element simulation of the model was carried out using ANSYS Workbench software, and the viscoelastic material parameters of cotton fibers were determined under different moisture content, the effects of different moisture contents and rotation speeds on the saw type gin stand were analyzed, and the stress and strain nephograms of cotton at different times were checked. The simulation results showed that when moisture content was between 6.1% and 7.8%, the ginning efficiency is the highest. The higher the speed of the saw tooth, the more severe the effect of ginning, but too high a speed will also affect the quality of the cotton lint. The results showed that the simulation conclusions were in line with the actual situation, and the model had certain application value.

Keywords

saw type cotton gin, ANSYS Workbench, finite element model

The saw type gin stand uses circular saw blades with high speed to drive the cotton fiber through the rib to separate the cotton fiber from the seed. The working principle of the saw type gin stand is to use more than 100 circular saw blades to grasp the cotton, and take the cotton through the fixed ribs. Because the cotton seed is larger than the rib gap, it is caught, so that the fiber and cotton seed are separated. The core of the saw type gin stand is the working box, and the core of the working box is the saw tooth and rib. The rib is fixed when operating, and the cotton fiber is pulled from the gap between the ribs by the rotation of the saw tooth to separate the cotton fiber and the cotton seed.¹ When operating the saw type gin stand, it needs to idle for about 2 minutes first. If there is no abnormality in the gin stand, then one can start to add unginned cotton, and check whether the cotton roll operates normally. Hughs et al.² introduced the important settings and adjustments of different types of gin stand. The gin breast, saws and doffing system were elaborated in detail. They proposed that it was paramount to

maintain the gin stand in good mechanical condition, to gin at recommended cotton fiber moisture levels of 6–7%, and to not exceed the capacity of the gin stand or other components of the system. Hughs and Armijo³ also carried on the test and the research to the different saw parameters in the gin stand, and found that there were important and significant differences between gin saws of different designs made for the same gin stand. These differences are related to processing efficiency in both the ginning process and the spinning process for higher quality ring-spun yarns. In order to analyze the influence of the number of saw blades in the gin stand

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on the quality of cotton, Ma et al.⁴ used the high volume instrument (HVI) to test the performance index and showed that the length, strength, and impurity of the cotton fiber processed by fewer saw blades are better than those of with multiple saw blades. Zhu⁵ analyzed the force on the cotton in the working box, and concluded that the geometry of the working box should accommodate as much cotton as possible, and the tangential resistance of cotton should be minimized to make the cotton run more smoothly. When the cotton moisture is high, the friction coefficient between cotton and the inner wall of the working box increases, as the friction increases, which is unfavorable to the processing. In the process of cotton ginning, under the pull action of the high-speed rotating serrated teeth, there is friction force and cohesion between fibers and the working conditions are relatively complex, so it is costly and difficult to directly measure the stress of the cotton fiber itself. Therefore, it is an efficient and feasible method to simulate the process of cotton ginning by finite element analysis. It can reduce the cost of experiments and improve their success rate.

The premise of using finite element analysis to simulate the process of cotton ginning is to establish a reasonable model on a computer. Dong⁶ used the experimental modeling method to establish a multi-objective model for the rotation speed of the feeding roller and toothed roller and the state of the seed cotton roll. The experimental modeling was carried out according to the operation data of saw type ginning. The modeling method adopted the least square support vector machine method, and the risk factor and kernel function width parameters in the least square support vector machine were optimized by the improved particle swarm optimization algorithm. Cao et al.⁷ explored the influence on ginning quality by testing the moisture content of the cotton. In order to explore the relationship between the ginning process and hand-picked cotton quality index, Li et al.⁸ took the ginning plant as the experimental field and hypothesized that there was a complex nonlinear relationship between the quality index of raw cotton and its influencing factors. Mourad⁹ used finite mixture models to derive a parametric expression of the fiber length probability density function. The model was applied to a multitude of empirical length distributions and proved to adequately parameterize the complex distribution patterns, as well as express the intrinsic and process-related factors determining their shape. Smith and Roberts¹⁰ calculated the motion of the textile fiber in the polymerized delivery pipe, assuming that the cotton fiber consists of a series of spherical elements connected by massless rigid rods. Although the fiber-fiber interaction was not considered, studies have shown that fibers can

straighten effectively in accelerated flow. Based on the idea of a composite laminated plate, Chen et al.¹¹ proposed the laminated plate cotton model, which assumed the inner cotton was composed of a certain number of layers of cotton fiber, and each layer of cotton fiber had a different arrangement angle. Based on the idea of three-dimensional four-way braided composite materials, Wang et al.¹² proposed a three-dimensional braided cotton model, considering the mutual entanglement among cotton fibers. The above two cotton models did not consider the existence of actual cotton seed, but represent cotton seed in the way of nodes. Based on the fractal principle, this paper proposes a new cotton model, namely a model with cotton seed.

Fractals represent an effective method to describe the geometric structure of irregular objects. Some researchers have used fractal methods to study the structure of fibrous materials. Fan et al.¹³ studied the thermal properties of wool fibers according to their fractal characteristics. The results show that both the temperature gradient and the rate along the temperature gradient of wool fiber are very slow, which indicates that wool fiber has good heat retention performance. Yang and Li¹⁴ introduced the concept of fractals into the structural characterization of wool fiber aggregates. Using the method of counting box dimension, the fractal dimensions of five wool fiber aggregates with different mass were calculated. Linking the fractal structure of wool fibers to their thermal properties, the relationship between the fractal dimension of fiber aggregate and its structural parameters, the thermal index is established. It is pointed out that the dimension close to the golden section is the reason why wool has excellent thermal insulation performance. Gao and Pan¹⁵ applied fractal theory to the description and quantitative characterization of feather fiber morphological structures, studied the fractal dimension of goose down fiber, and observed and calculated the internal structure of feather aggregation based on fractal theory. Kan et al.¹⁶ established a mathematical model to predict the thermal conductivity of glass fiber based on fractal theory. By comparing the experimental test and theoretical calculation, the functional relationship between the thermal conductivity of porous media under vacuum and the micro-scale spatial structure of porous media and the pressure inside the plate was reflected, and the relationship between its thermal properties and the internal micro-scale spatial structure was established. It shows that many fiber structures can be assumed by fractal theory. The cotton model is a very complex and is in a chaotic state with no rules. It is difficult to establish a model based on its growth rules, and there is no literature to refer to. As cotton also has fiber, this paper attempts to establish a cotton model based on fractal theory from

the perspective of the distribution of cotton fibers by observing Xinluzhong 37 cotton, and approximately represents the random distribution of cotton fiber through the regular model. Finally, the simulation results of the model are compared with the experimental results; the results are within a reasonable error and so confirm the rationality of the model.

Establishment of the cotton model

The morphological structure of cotton

In order to establish a complete model with cotton seed, it is necessary to observe the shape of cotton. The observed cotton variety was Xinluzhong 37, because it had good cultivation performance and was widely planted in Xinjiang province. The length of the cotton is about 28.7 mm, and the micronaire value is 4.1. The uniformity index (UI) was 81.5%, the short fiber index (SFI) was 13.9%, the strength (Str) was 21.1 Cn/tex, and the elongation (ELG) was 7%.¹⁷ Visually, the distribution of cotton fiber is disordered. Generally, cotton fiber is distributed radially with cotton seed as the center. Through observation, it was found that the closer the part is to the cotton seed, the denser the cotton fiber distribution was, and the greater the relative density of the cotton fiber bundle is, the more the color is white and milky white. The cotton seed in the middle is an irregular ellipse.

In order to further observe the structure of the cotton, some fibers on the surface of the cotton were removed without affecting the structure of other fibers, and the distribution of the fiber was observed with a 20 times magnifying glass. As shown in Figure 1, one end of the fiber grows from the surface of the cotton seed, while the other end becomes fiber bundles together with other adjacent cotton fibers, or each of them is distributed independently in a space. Some of these end cotton fibers are interlaced longitudinally like a net, while others are distributed radially outward, similar to the bifurcation of a tree. This is one reason why cotton looks out of order. Cotton fibers are distributed in all directions of the three-dimensional space, and there are gaps between the fibers, indicating that the fibers are not tightly pressed together.

At the macro level, the shape of cotton resembles an irregular ball. In terms of its internal structure, cotton fibers are distributed in all directions of three-dimensional space, with different lengths of cotton fibers, a messy layout, and intricate layers, making it difficult to find their rule. In order to observe the distribution of cotton fiber in a more specific way, Scharr edge detection was carried out with image processing software, as shown in Figure 1, and the test was repeated. The results are shown in Figure 2. From the center, the



Figure 1. Enlarged view of cotton.

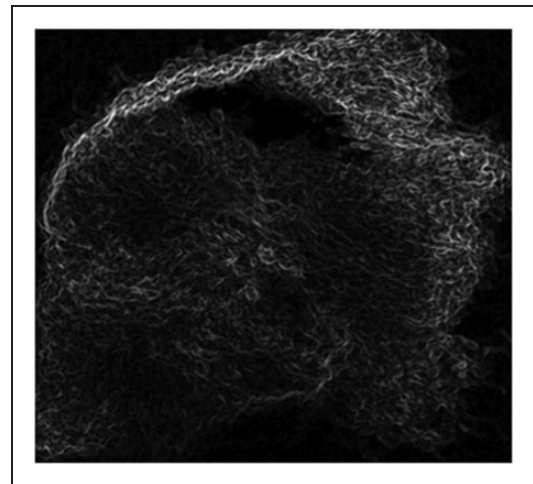


Figure 2. Edge detection image.

relative density of cotton fiber is the highest and it is easy to form cotton fiber bundles. The closer to the edge, the more obvious the extension of the cotton fiber is. Visually, it is just like branches growing outward. In addition, there is a strong similarity between one fiber and another, different lengths, and slightly different thicknesses.

Fractal theory is one of the more active theories in scientific research. Its essence refers to the characteristics of some irregular and separated objects, which are used to analyze some nonlinear and irregular geometric shapes in nature. In this paper, a new cotton model with cotton seed is proposed based on fractal theory.

Fractal cotton unit and cotton seed model

According to observation and the literature,¹⁸ cotton seed is an ellipsoid with a two-layer structure, the

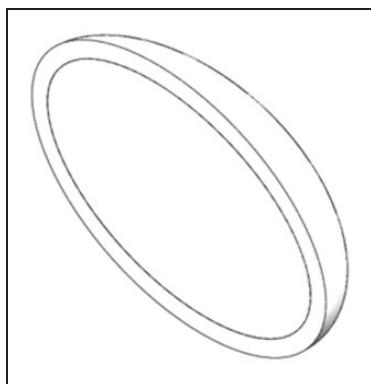


Figure 3. Sectional view of the cotton seed model.

outer layer is cotton seed shell, and the inner layer is cotton seed kernel. In order to make the simulation model more consistent with reality, this paper took the actual measured average value of Xinluzhong 37 to conduct modeling (length $L=10$ mm, width $B=6$ mm). There are some differences in the thickness of the cotton seed shell in all directions, but it is smaller than the overall size of cotton seed and the overall cotton size. In order to simplify the model, the cotton seed shell is simplified to an equal thickness shell, and the average thickness measured by experiment is 0.52 mm. A sectional view is shown in Figure 3.

Then a cotton unit generated by fractal theory (the fractal cotton unit) will be produced. It is difficult to generate the fractal model in three-dimensional space directly by using the modeling software. In order to generate a three-dimensional cotton model, a two-dimensional fractal plane graph of cotton is drawn from the top view and the front view. Then, based on the two fractal views and combined with the experiment to observe the size of cotton, the fractal cotton unit in three-dimensional space was drawn, as shown in Figure 4. The fractal cotton unit is evenly distributed on the cotton seed and, finally, the fractal-based overall cotton model containing cotton seed is generated, as shown in Figure 5. The specific process is shown in the Appendix.

The selection of parameters of the moisture content in the finite element simulation

Moisture content is an important parameter in cotton processing. During cotton processing, if the moisture content is too high, the friction coefficient on the surface of the cotton fiber will increase, and it is difficult to remove impurities such as dust and trash from the surface of cotton fiber, which affects the cotton grade. If the moisture content is too low, the cotton fiber will be relatively fragile, and will more easily break when

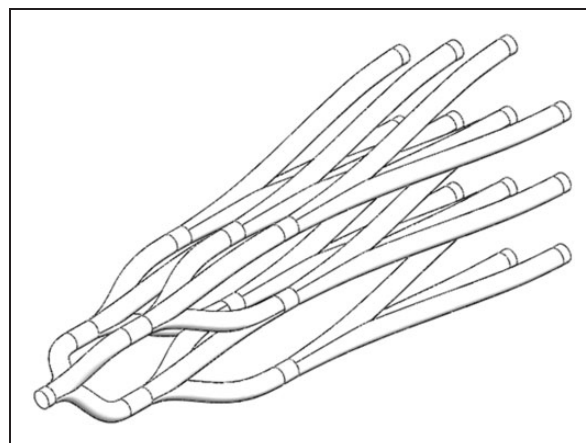


Figure 4. Fractal cotton unit.

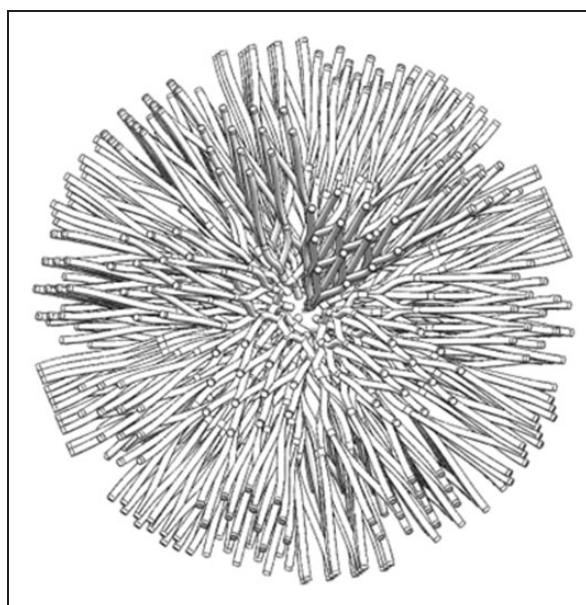


Figure 5. Cotton model with cotton seeds.

passing through the saw type gin stand and lint cleaning machine, increasing the short fiber and nep content. Therefore, in the whole process of storage and processing of cotton, if the control of moisture content is not appropriate, it will eventually cause the decline of the lint grade and the loss of cotton value.

Wang¹⁹ conducted stress relaxation performance experiments of cotton fiber under different moisture recovery rates, described the mechanical performance of cotton fiber through Burgers mechanical model, and used 1stOpt software and MATLAB software to fit the stress relaxation equation in combination with experimental data to obtain the values of various parameters in the viscoelastic model, as shown in Table 1.

Table 1. Stress relaxation parameters of cotton fibers under different moisture contents

Moisture content/%	$E_1/\text{cN} \cdot \text{dtex}^{-1}$	$E_2/\text{cN} \cdot \text{dtex}^{-1}$	$\eta_1/\text{cN} \cdot \text{s} \cdot \text{dtex}^{-1}$	$\eta_2/\text{cN} \cdot \text{s} \cdot \text{dtex}^{-1}$
5.2	158.295	27.037	681.715	19,880.471
6.1	164.095	25.883	691.573	29,091.795
7.8	159.873	25.439	671.215	27,103.253
9.1	150.915	24.346	608.535	21,348.383

Table 2. Viscoelastic material parameters of cotton fibers at different moisture contents

Moisture content/%	Relaxation time/s	$G_0/\text{cN} \cdot \text{dtex}^{-1}$	G_0/MPa	β/s^{-1}
5.2	3.676	13.518	883.569	0.272
6.1	3.639	12.941	845.841	0.274
7.8	3.620	12.719	831.346	0.276
9.1	3.470	12.173	795.627	0.288

Cotton fiber is a viscoelastic material. In the explicit dynamics of ANSYS Workbench software, viscoelastic material uses instantaneous shear modulus G_0 and attenuation constant β to describe material relaxation. The above parameters are transformed into variables in the formula²⁰ to obtain the viscoelastic parameters required by simulation, as shown in Table 2.

The cotton ginning experiment

As in the actual process of cotton, the ginning box is closed. It is equivalent to a black box and it is difficult to observe the internal work directly from outside. The ginning itself is a dynamic process. The stress and displacement on the serration and the lap are changing from time to time and it is difficult to extract the information from the moving object. Therefore, in order to be able to research the process of ginning, this paper in accordance with the research of the actual structure of the ginning box designs a device. The device can simulate the ginning process, but the structure is much simpler than the actual gin stand.

The following are some of the relevant parameters of the small saw type gin stand used in this paper: the space of the two rib work at the work point was 2.8–3.2 mm; the outside diameter of the saw blade was 320 mm; the drum diameter and inside diameter of the saw blade were 64 mm; the center distance of the two saw blades was 19.4 mm; and the quantity of seed cotton processing was 300 kilograms per hour. According to the actual parameters, the experimental device is designed by changing the ginning part of a single saw blade and a small amount of seed cotton in

the form of action to simulate the work inside the ginning work box. The overall experimental setup is shown in Figure 6. The purpose of the experiment is to measure how much force the seed cotton will bear when the cotton fiber is pulled off from the cotton seed and taken away by the saw blade. A steel saw blade is used in the device, which has 303 teeth. A hook is attached to the edge of the saw blade near the lower part of the cylinder for hanging weights. The saw blade is positioned through the shaft. The shaft is mounted on the bracket by a rolling bearing. The other end of the bracket is placed on the cylinder and cotton is arranged in the cylinder to be rolled. The cylinder and the bearing have the proper installation distance to ensure the relative position of the saw blade and the seed cotton. The middle of the cylinder has a 3 mm gap to simulate that between the rows of the embossed ribs so the saw blade can be inserted into the gap with the seed cotton. The width of the gap is slightly smaller than the size of the cotton seed to make sure the cotton seed does not fall.

Before the experiment, the seed cotton with moisture content of 7.8% was put into the cylinder. The saw blade is rotated into the serration in full contact with the seed cotton, before being inserted into the slot just above the hook. At the beginning of the experiment, a bag with a certain amount of sand is hung on the hook. A smaller sand mass is selected when the bolt is hung for the first time and the contact between the saw blade and the cotton fiber in the cylinder is observed. The sandbag directly provides the pulling force for the saw blade and acts on the cotton flower. When the weight of the sandbag is gradually increased, the force acting on the cotton flower increases as well. The final force is increased to pull the cotton fiber from the cotton seed and the cotton fiber is taken away by the rotating saw blade. The cotton seed is left inside the cylinder because it is larger than the gap size. When the cotton fiber is pulled by the saw blade, the weight of the sandbag is the final force on the cotton and the force is recorded as the result of the experiment. It should be noted that a single serration should only hook a cotton fiber on a cotton to match the subsequent finite element model. Because a single serration is much smaller than a single cotton flower, the condition is easy to meet.

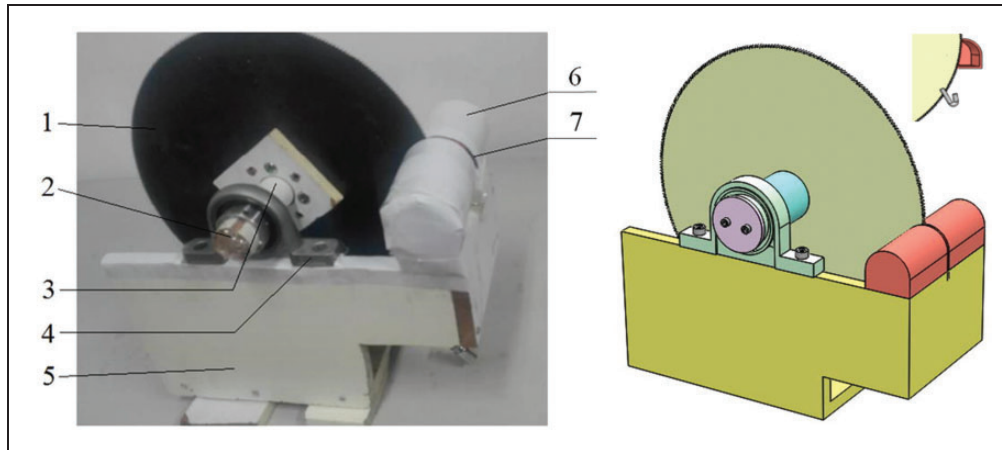


Figure 6. Ginning experiment device: (1) saw blade; (2) shaft; (3) axle sleeve; (4) roller bearing; (5) bracket; (6) cylinder; (7) cylinder gap.

In order to reduce the error caused by chance, it is necessary to carry out several experiments and take the average. After each experiment, the cotton fiber on the serration is brushed off. The seed cotton in the cylinder needs to be removed and new seed cotton re-installed into the cylinder. After performing experiments and removing the failed data, the remaining data are collated as shown in Table 3. The average value of the 12 experimental data was 175.399 g, so the force was 1.719 N.

Finite element simulation of a saw type cotton gin

On the saw type gin stand, the saw tooth can only touch half of each cotton at most. In order to save the simulation cost, half of the fractal model containing cotton seeds is taken for simulation. The model is imported into the Explicit Dynamic module of ANSYS Workbench. Since the cotton fiber grows directly from the cotton seed, the cotton fiber and the cotton seed need to use a conjugate grid to combine the cotton fiber and the cotton seed into one part, that is, the joint node is shared at the contact surface.

Finite element analysis of the cotton model with cotton seed

In the pre-processing of finite element simulation, the cutter is set as a rigid body, and the cotton fiber and seeds are set as flexible bodies. The cutter was divided into hexahedral meshes and the mesh of the contact surface was refined. The refined mesh size was 5×10^{-4} m. The structure of the cotton fiber is irregular, which is divided by tetrahedral mesh. The overall mesh size is 5×10^{-4} m, and the mesh size in the intense working area is refined to 3×10^{-4} m. The divided grid is

Table 3. Experimental data of cotton ginning

Weight of the sandbag (g)				Average (g)
153.56	177.95	148.40	167.07	175.399
179.94	177.62	170.05	179.16	
201.61	191.82	177.71	179.90	

shown in Figure 7. The average element quality is 0.828, and the average orthogonal quality is 0.856, which is greater than 0.7. The closer the value is to 1, the better the mesh quality is, and a value lower than 0.7 needs to be corrected. This shows that the mesh quality is better and can be simulated subsequently.

The material parameters that needed to be defined in the simulation are shown in Table 4, and the viscoelastic parameter was set to $G_0 = 831.346$ MPa, $\beta = 0.2762$. The freedom of the saw tooth in five directions is restrained so that it can only move around the axis, and the rotation speed of 435 rpm is converted into angular velocity and applied to the saw tooth. When the saw type gin stand is working, the saw teeth hook the fiber to rotate. When it passes through the ginning rib, the larger size of the cotton seed is caught between the ribs, while the cotton fiber can pass through the ribs, so that the cotton fiber and the cotton seed can be separated. The work box is composed of the ginning rib and the rib row of the blocking shell, the lap plate, the movable cover plate, and the breast plate, which is the core part of the saw type gin stand. The cotton seed full constraint represents the cotton seed limited by the ginning rib. The mass scaling and material erosion failure switches were turned on. The solution time is set to 3.64×10^{-3} s.

When the solution is completed, we take the stop time $t = 3.64 \times 10^{-3}$ s, as shown in Figure 8; in order

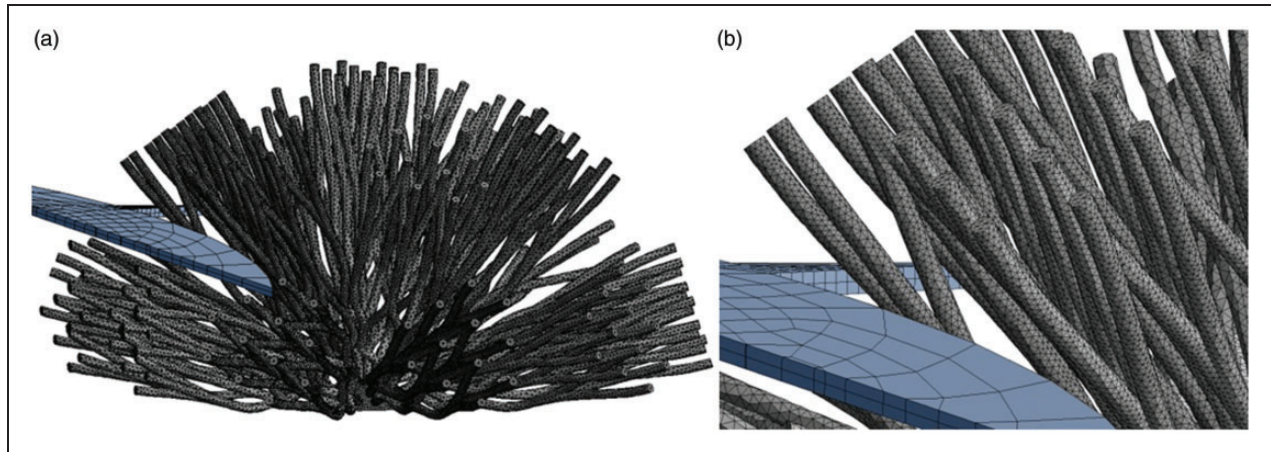


Figure 7. Global mesh (a). Locally enlarged mesh (b).

Table 4. Material parameters

Material	Young's modulus (MPa)	Poisson's ratio	Density (kg/m ³)
Saw tooth	200,000	0.30	7850
Cotton	2400	0.40	400
Cotton seed	11	0.33	500

to observe the stress of the cotton in detail, the saw tooth part is hidden and only cotton is displayed. The stress and strain nephogram are viewed at different times. It was found that large deformation occurred in the region of fibers directly acting on the saw tooth. The amount of deformation of the cotton fiber increases with time until the saw tooth action causes the fiber to fall off the seed. It can be seen that the cotton area in direct contact with the saw tooth has a great change in stress, most of which is light blue and blue, while the remaining areas are basically dark blue. This is due to the fact that although there is an interaction force between the cotton, the force is relatively small compared to the cotton area in direct contact with the saw tooth, so the cotton is shown in dark blue.

To facilitate observation, the cotton areas in direct contact with the saw tooth at different times are enlarged and are shown in Figures 9 and 10. The stress and strain of the cotton fiber at different moments and the strain of the cotton seed at different moments can be obtained, as shown in Table 5. From the stress distribution nephogram, it can be seen that the affected area on the cotton fiber increases with time. According to the figures and table, when $t = 6.872 \times 10^{-4}$ s, the saw teeth begin to contact the cotton fibers, the force range is relatively small, and the stress and strain are also small. At this time, the saw blade continues to rotate, the number of cotton fibers in

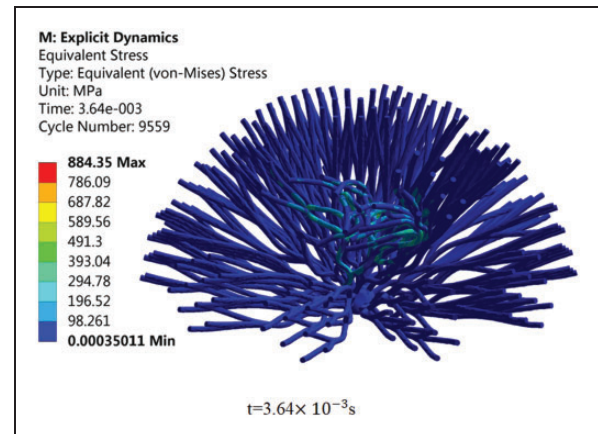


Figure 8. Stress nephogram of the cotton at different times. (Color online only.)

the hook gradually increases, and the stress continues to increase. When the time reaches $t = 1.593 \times 10^{-3}$ s, it is found from the stress and strain nephogram that some fibers start to fall off from the cotton seed; the strain of some cotton fibers reached more than 12%, and the maximum strain of cotton seeds reached 56.21%, which is greater than the fracture rate of 7–8%, indicating that the raw cotton begins to form. From $t = 1.593 \times 10^{-3}$ to $t = 2.503 \times 10^{-3}$ s, the stress value and the stress area show a gradual increasing trend, which is because the number of cotton fibers that have been pulled off by the saw tooth continues to increase. The cotton fiber material is soft in texture and has good deformation performance. When the saw tooth contact with the cotton fiber is less, it is more difficult for the force of the saw tooth to fully act on the cotton fiber, and the fiber bears less stress. When more cotton fibers are contacted, the interaction

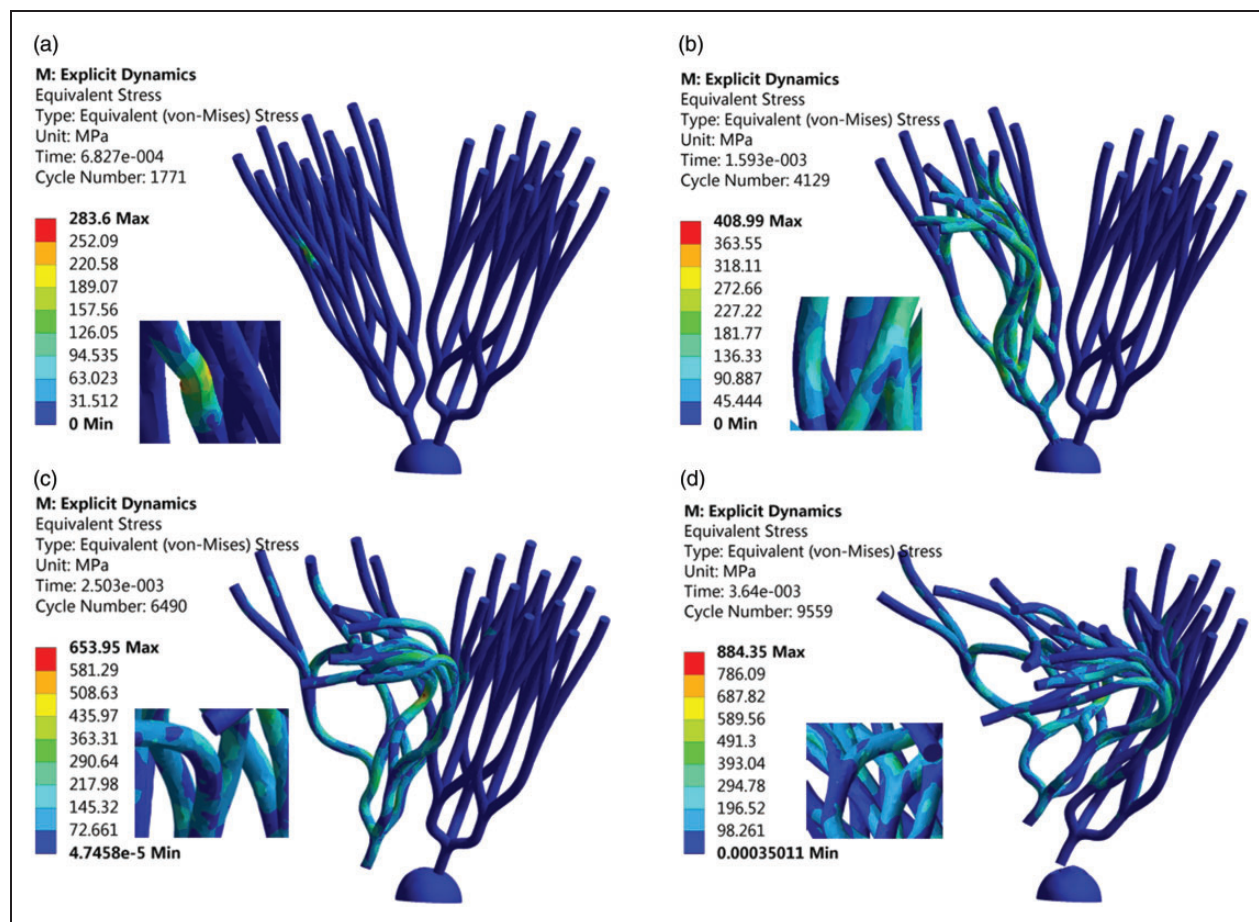


Figure 9. Enlarged stress nephogram of cotton at different times: (a) $t = 6.827 \times 10^{-4}$ s; (b) $t = 1.593 \times 10^{-3}$ s; (c) $t = 2.503 \times 10^{-3}$ s; (d) $t = 3.64 \times 10^{-3}$ s. (Color online only.)

between the contact fibers becomes more and the structure becomes stronger, which makes it easier for the saw tooth force to act on the cotton fibers. Therefore, with the increase of saw tooth contact with the cotton fiber, the stress value gradually increases and the stress area also increases.

The stress reaches its maximum when $t = 3.64 \times 10^{-3}$ s. It can be seen from the stress nephogram of the model that the stress distribution on the cotton fiber is directly related to the saw tooth. Most areas of the cotton fibers are dark blue, blue, and light blue, with stress between 98.261 and 294.78 MPa. A few areas are green, yellow, or red, and the stress is above 294.78 MPa. The stress distribution on the cotton seed is generally dark blue, which is much lower than 98.261 MPa. From the strain nephogram of the model, it can be seen that most areas of the fiber bundles affected by the saw tooth are blue and light blue. The strain of the blue area is between 6.300% and 12.601%, and the strain of the light blue areas is between 12.601% and 18.901%. The strain of other parts of the cotton fiber bundle is small, showing dark blue, indicating strain below

6.300%. The maximum strain of the cotton seed occurred at the junction of the cotton fiber and cotton seed, showing red and orange. The strain of the red region is 50.404–56.704%, and that of the orange region is 37.80–50.404%. In addition, the closer to the connection of the cotton fiber and cotton seed, the larger the strain in the strain nephogram, showing regional variation. The maximum strain of the cotton fiber and single saw tooth interaction reaches 12.601%, the maximum strain of the cotton seed and cotton fiber joint reaches 56.704%, and the fracture rate of the seed cotton is 7–8%. Based on the assumption of material continuity in finite element analysis, it can be seen that raw cotton has been formed before cotton reaches this strain in actual processing.²¹

From the stress-strain nephogram, it can be seen that during a short period of time from $t = 0$ to $t = 1.593 \times 10^{-3}$ s, the saw tooth slowly contacts the cotton fibers, but no cotton fibers are pulled off from the cotton seeds by the saw teeth, and the stress and strain increase gradually. After that, the strain value is

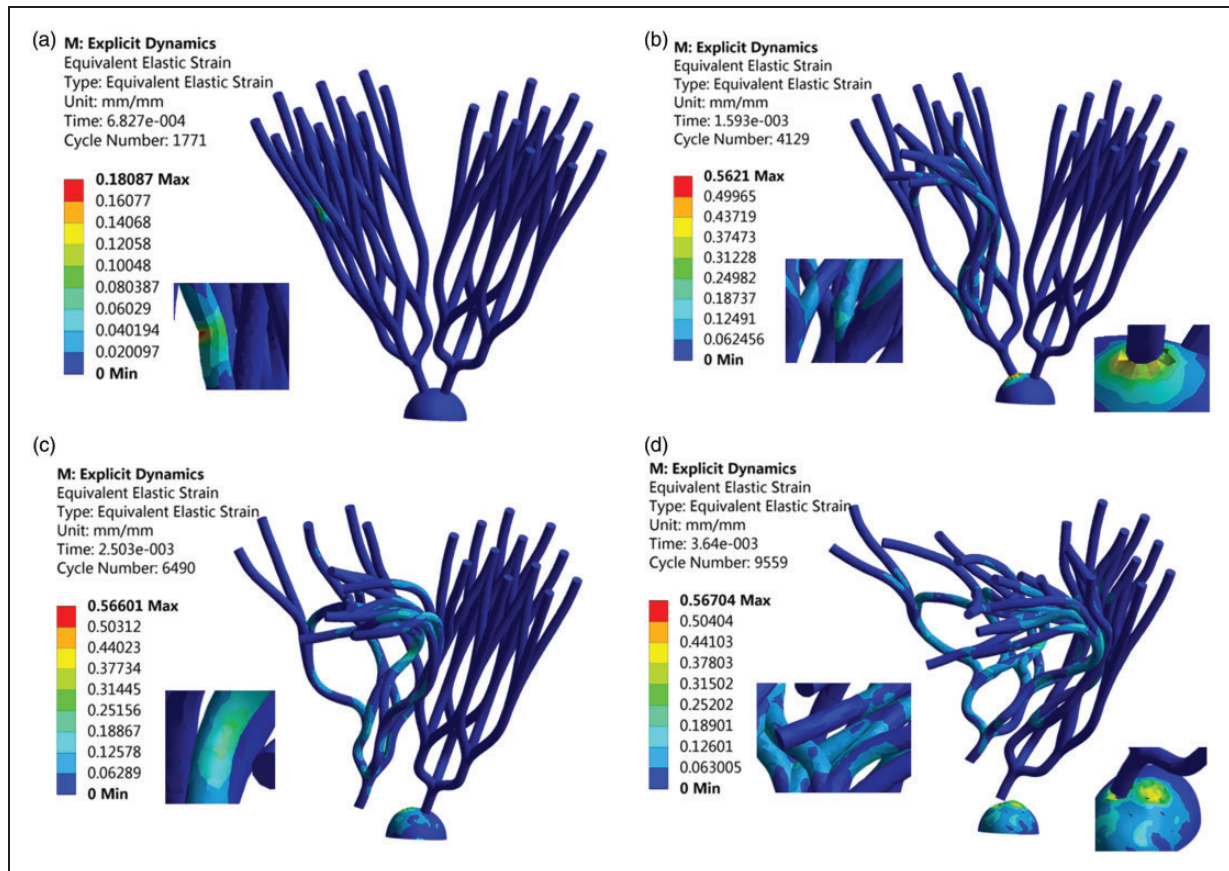


Figure 10. Enlarged strain nephogram of cotton at different times: (a) $t = 6.827 \times 10^{-4}$ s; (b) $t = 1.593 \times 10^{-3}$ s; (c) $t = 2.503 \times 10^{-3}$ s; (d) $t = 3.64 \times 10^{-3}$ s. (Color online only.)

Table 5. Stress and strain of cotton at different times

Time (s)	Cotton fiber stress (MPa)	Cotton strain (%)	Cotton seed strain (%)
6.827×10^{-4}	31.51–94.53	2.01–6.03	18.08
1.593×10^{-3}	45.44–136.33	6.24–18.73	56.21
2.503×10^{-3}	72.66–217.98	6.29–18.86	56.60
3.640×10^{-3}	98.26–294.78	6.30–18.90	56.70

relatively stable for a long period from $t = 1.593 \times 10^{-3}$ s to the stop time. At this stage, the fibers are continuously pulled from the cotton seed by serrated teeth, and the stress gradually increases. According to the mechanical properties of cotton fiber, the connection force of machine-picked cotton is 78 MPa. The median value of breaking strength is 151.3 MPa. The 10th percentile of breaking strength is 104.1 MPa and the average value of breaking strength is 148.1 MPa. In Figure 9, with the increases of stress, the connection force value of the cotton fiber to seed is achieved first. This part of the stress is smaller so that the cotton fibers

are not snapped in a single hook. At this point, the cotton ball rolled together with the cotton seed to leave the row of ginning ribs and wait for the next hook. As the stress continued to increase, the breaking strength, average value, and median value of the cotton fiber are sequentially reached. The cotton fibers are affected by the impact of the saw bit, leading to more and more cotton fiber breakage and resulting in the formation of short fibers. It can be seen that the simulation results are in good agreement with the actual ginning process. In addition, in the case of large deformation, the stress between the cotton fiber and cotton seed changes below 98.261 MPa, while the stress between cotton fiber and cotton seed changes between 98.261 and 196.52 MPa when the cotton fiber itself breaks.

Through the post-processing of finite element simulation, the force of the serration surface is observed and the force of the bottom surface of the serration is obtained. The specific force is shown in Figure 11. It can be seen from the figure that the maximum force received by the bottom surface of the serration is 1.9367 N. According to the third law of Newton,²² the maximum force of cotton is 1.9367 N. Through the

experiment of cotton ginning, it can be concluded that the force required when the cotton fiber is broken by serration is 1.719 N. Compared with the experimental results, the error between the simulation results and the experimental results was 12.67%, and the error was small, which shows that the fractal cotton model has certain rationality.

The effect of moisture content on the process of ginning

Under the condition that the working rotation speed is 435 rpm, the moisture content of cotton is 5.2%, 6.1%, 7.8%, and 9.1%, respectively. Repeating the above finite element simulation, taking the stop time $t = 3.64 \times 10^{-3}$ s, and taking the cotton with a moisture content of 5.2% as an example, the stress and strain nephogram of the cotton, as shown in Figure 12, is obtained after

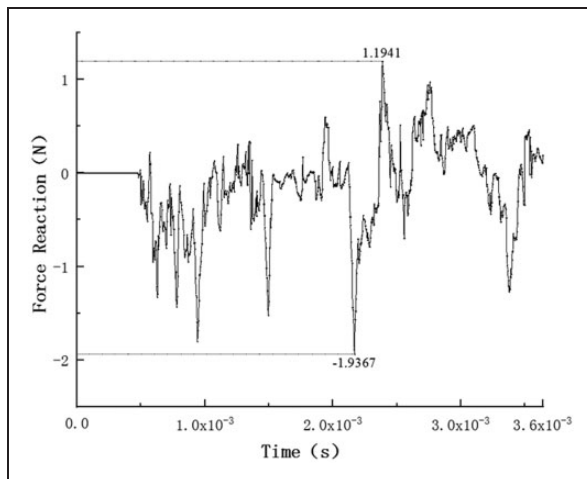


Figure 11. The node reaction force of the saw tooth of the gin.

amplification (Figure 12(a) shows the stress nephogram and Figure 12(b) shows the strain nephogram). See Table 6 for details after finishing.

In the finite element simulation, the moisture content is controlled. Since the angle of the screenshot is slightly different in the post-processing of finite element simulation, it is more obvious to observe that the cotton fibers have been separated from the seeds. From the stress nephogram in Figure 12, it can be seen that the stress distribution of the cotton fiber bundles mainly affected by the saw tooth is dark blue, blue, and light blue when the moisture content is 5.2%. The stress changes are between 86.86 and 260.56 MPa. A few areas are green, yellow, and red, and the stress changes are greater than 260.56 MPa. The stress on the cotton seed is still very small, much lower than 86.86 MPa. From the strain nephogram, it can be seen that the maximum strain on cotton seed is still at the junction of the cotton fiber and cotton seed, and the maximum strain is 56.58%. Most areas of the cotton fiber bundle under the action of the saw tooth are dark blue, blue, and light blue, with strains ranging from 6.31% to 18.88%. Compared with the previous finite element analysis of 7.8% moisture content, the main stress

Table 6. Cotton stress and strain conditions at different moisture contents

Moisture content (%)	Cotton fiber stress (MPa)	Cotton fiber strain (%)	Cotton seed strain (%)
5.2	86.86–260.56	6.31–18.88	56.58
6.1	93.62–280.85	6.32–18.88	56.55
7.8	98.26–294.78	6.30–18.90	56.70
9.1	89.04–267.12	6.31–18.91	56.69

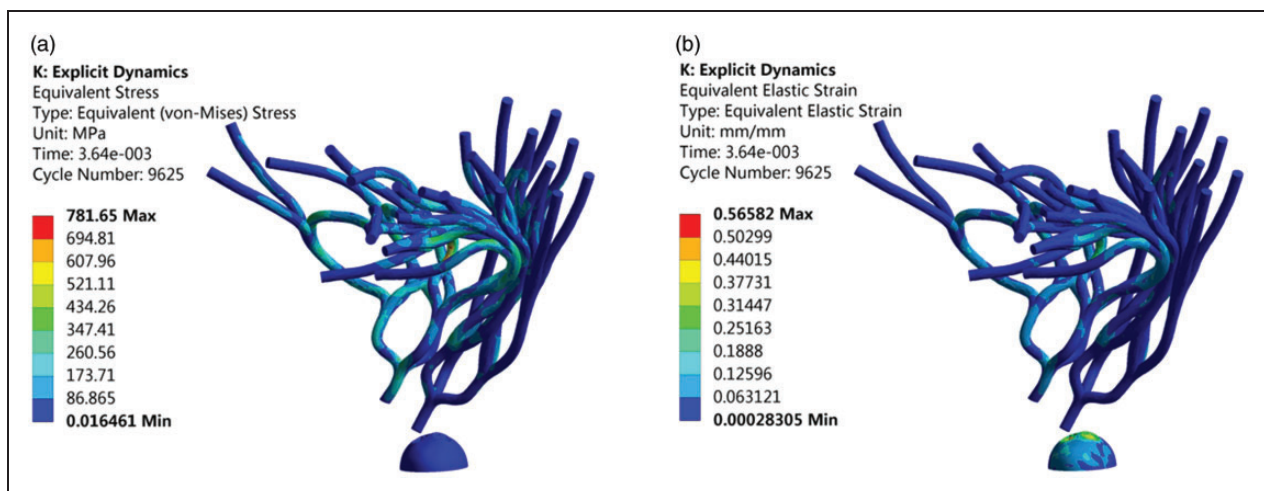


Figure 12. Stress and strain nephograms of the model at 5.2% moisture content. (Color online only.)

and strain trends of cotton at 5.2% moisture content are roughly the same. In addition, the trend of stress on cotton under other moisture content conditions is the same. When the moisture content is 6.1%, the stress of cotton varies from 93.62 to 280.85 MPa, and the strain varies from 6.32% to 18.88%. When the moisture content is 7.8%, the stress of cotton varies from 98.26 to 294.78 MPa, and the strain varies from 6.30% to 18.90%. When the moisture content is 9.1%, the stress of cotton varies between 89.04 to 267.12 MPa, and the strain is between 6.31% and 18.91%. Longitudinal comparison shows that when the moisture content changes, the stress on cotton changes slightly. When the moisture content is between 6.1% and 7.8%, the stress on cotton is relatively high. Therefore, it can be considered that the efficiency of cotton ginning is the highest under this moisture content.

The effect of rotation speed on the process of ginning

In actual working conditions, the rotation speed of the saw type gin stand is a very important factor affecting the efficiency of cotton ginning. Controlling reasonable rotation speed can improve the quality of lint. Under the condition that the moisture content is controlled at 7.8%, the rotation speed of the saw tooth is taken as 435, 507, 580, 652, and 725 rpm, respectively. The stress and strain nephograms of cotton and saw tooth action under different rotation speeds were obtained by repeating the above finite element analysis with other conditions unchanged, taking the speed of 580 rpm as an example (Figure 13(a) shows the stress nephogram and Figure 13(b) for the strain nephogram). See Table 7 for details after finishing.

From Figure 13, the stress and strain of cotton fibers and cotton seed at different rotational speeds can be

obtained, as shown in Table 7. According to the figures and table, the strain of cotton fiber and cotton seed reaches about 12% and 56%, respectively, both of which reach the fracture rate of seed cotton when it was fractured, indicating that the five kinds of cotton ginning speeds could make cotton fiber be pulled off from cotton seed, which was in line with the actual situation of cotton ginning. Moreover, the faster the rotation speed of the saw tooth, the greater the maximum stress on the cotton fiber, and the more violent the action between the saw tooth and the cotton fiber. In addition, the green and yellow areas where large strains occur in strain nephograms also increase. Therefore, the simulation results show that the work efficiency of ginning can be improved by increasing the rotation speed of the saw tooth. However, the rotational speed should not be too high. When the rotational speed is high, the area of large stress will increase, and the impact force will increase in the actual situation, which will break the cotton fibers and affect the quality of the raw cotton. Therefore, the ginning speed is not the larger the better.

Table 7. Cotton stress and strain conditions at different rotational speeds

Saw tooth rotation speed (rpm)	Cotton fiber stress (MPa)	Cotton fiber strain (%)	Cotton seed strain (%)
435	70.54–211.64	6.30–18.90	56.70
507	81.25–243.74	6.31–18.89	56.64
580	81.92–245.75	6.30–18.99	56.69
652	88.93–266.80	6.31–18.91	56.71
725	91.89–275.67	6.29–18.89	56.67

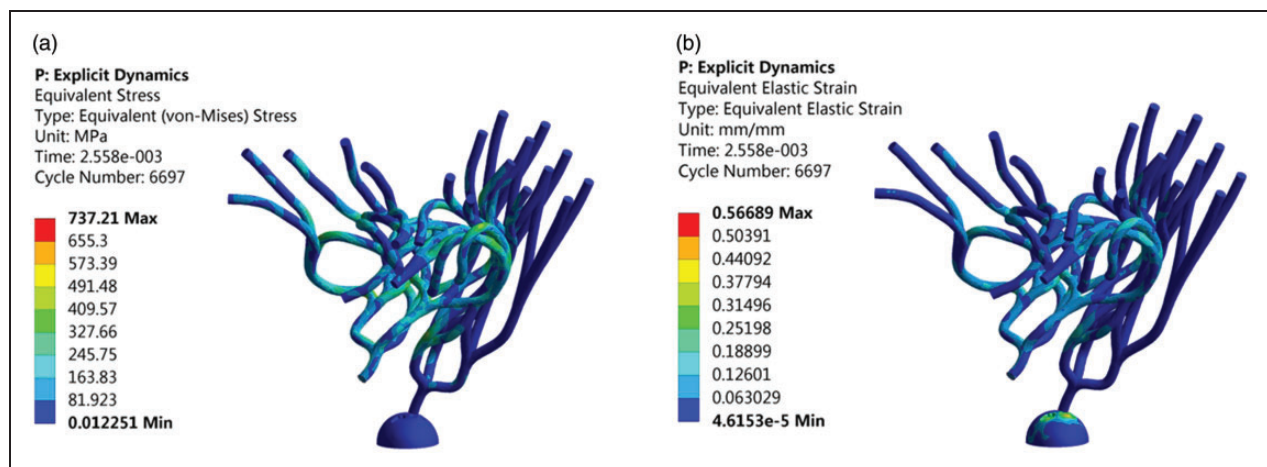


Figure 13. Stress and strain nephograms at 580 rpm rotational speed. (Color online only.)

Conclusion

The process on the saw type gin stand was analyzed, and the following conclusions can be drawn from the analysis.

1. On the basis of the laminated cotton model and three-dimensional braided cotton model, the whole cotton model containing cotton seeds was constructed by observing cotton and using the fractal principle. Neither the laminated cotton model nor the three-dimensional braided cotton model considers the actual distribution of cotton seed, but only uses the control node to carry out the central constraint in the finite element simulation, assuming the existence of cotton seed. The fractal cotton model with cotton seed not only considers the interaction between fiber bundles, but also establishes cotton seed directly in the three-dimensional model, which is more in line with the actual situation in terms of structure.
2. Finite element simulation was carried out on this model with ANSYS Workbench, and the stress state of the cotton fiber and cotton seed during the ginning process was successfully described. The working condition of the saw type gin in different time periods is obtained, which is consistent with the actual working conditions. The action stress between the cotton fiber and cotton seed is lower than the action stress between the cotton fiber and cotton seed, which verifies the rationality of the model.
3. By simulating the influence of different moisture contents and saw tooth rotation speeds on the process of ginning, it is concluded that when moisture content is between 6.1% and 7.8%, the ginning efficiency is the highest. The higher the speed of the saw tooth, the more severe the effect of ginning, but too high a speed will also affect the quality of raw cotton. Therefore, for the cotton variety Xinluzhong 37, the finite element simulation of the cotton ginning process has a certain reference value for the selection of working conditions and the determination of parameters in actual production.

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Appendix

The generation of the cotton model

The attractors of Iterated Function System (IFS) are generally fractal, which is called deterministic fractal. The process of the IFS generating fractal

Table 8. IFS transformation of fractal cotton unit in top view

T_i	ω_i	
T_1	$x' = x - 1.25$	$y' = y + 2.17$
T_2	$x' = x - 1.25$	$y' = y - 2.17$
T_3	$x' = x + 2.5$	$y' = y$

Table 9. IFS code of fractal cotton unit in top view

i	a_i	b_i	c_i	d_i	e_i	f_i
(1)	1	0	0	1	-1.25	2.17
(2)	1	0	0	1	-1.25	-2.17
(3)	1	0	0	1	2.5	0

graphics starts with simple composition and is completed through a series of iterations. Using IFS theory²³ and actual cotton size, in the two-dimensional plane of the top view, the three compression mappings ω_i are as shown in Table 8. The IFS code is shown in Table 9.

Figure 14(a) is a graph of the initial set: region ① is obtained by ω_1 transformations of the initial set graph (a). In the same way, regions ② and ③ are obtained by ω_2 and ω_3 transformations of the initial set graph (a), respectively.

In the two-dimensional plane of the front view, the three compression mappings ω_i are respectively shown in Table 10. IFS codes are shown in Table 11.

The initial graph and iteration process are shown in Figure 15. Deterministic algorithms are simple in principle, but do not consider the difference between each

Table 10. IFS transformation of fractal cotton units in the front view

T_i	ω_i	
T_1	$x' = x + 2.5$	$y' = 2y + 4$
T_2	$x' = x$	$y' = 2y + 4$
T_3	$x' = x - 2.5$	$y' = 2y + 4$

Table 11. IFS code of the fractal cotton unit in the front view

i	a_i	b_i	c_i	d_i	e_i	f_i
(1)	1	0	0	2	2.5	4
(2)	1	0	0	2	0	4
(3)	1	0	0	2	-2.5	4

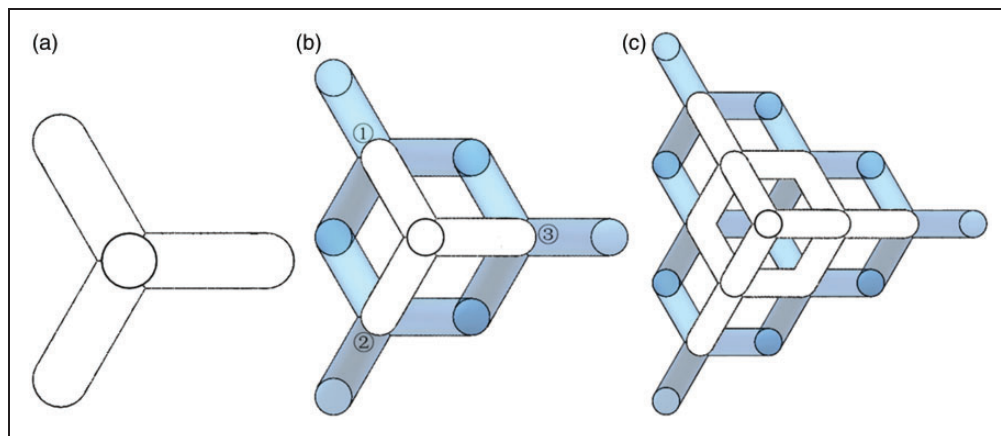


Figure 14. Initial graph and transformation process of the top view: (a) graph of the initial set; (b) $n = 1$; (c) $n = 2$.

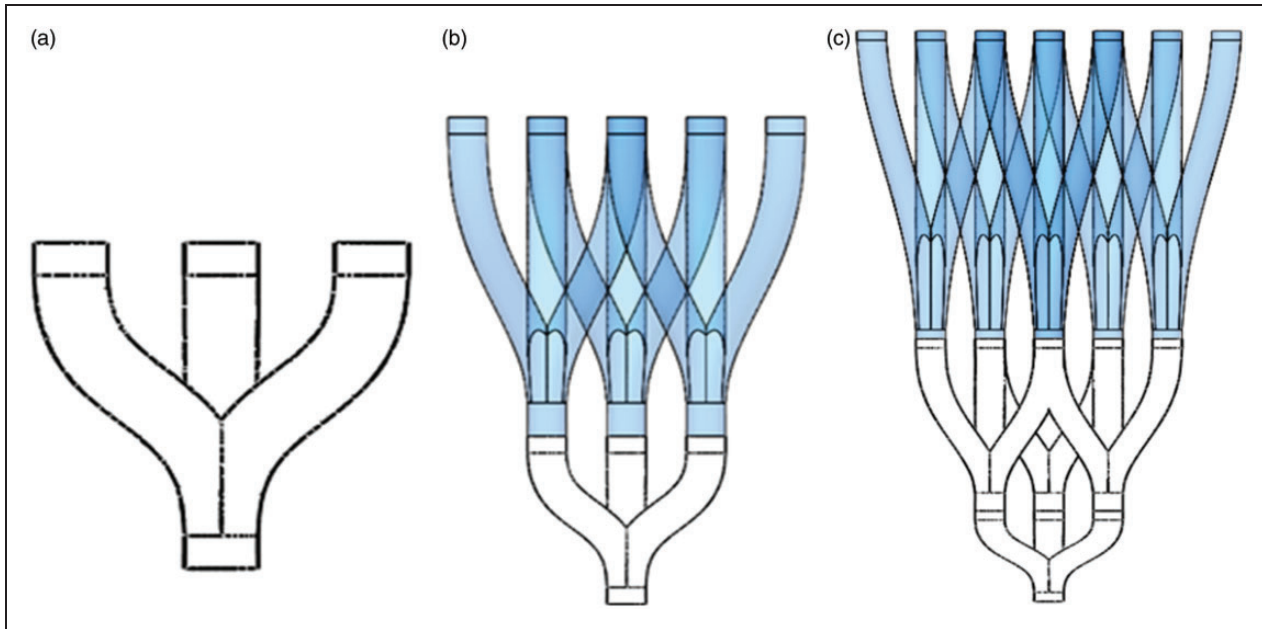


Figure 15. Initial graph and transformation process of the front view: (a) initial set graph; (b) $n = 1$; (c) $n = 2$.

compression mappings ω_i , so in the iteration, each compression mapping is on an equal footing.

The iterative process can be seen in Figures 14 and 15. The more iterations, the more obvious the fractal features and the larger the space filling proportion. However, the more iterations, the more geometric features of the model are obtained. When the number of iterations reached three times ($n = 3$), the features of the generated model showed a geometric multiple increase. Due to the limitation of the finite element software, the generated model is too complex in the finite element simulation of the ginning process, reaching the critical value of the finite element software identification

features, and it is difficult to import the model and divide the mesh. Therefore, in order to simplify the cotton model, making it conducive to simulation, some unnecessary geometric features are ignored, such as the assumption that the fiber bundle section is circular, which can avoid the occurrence of chamfering. The figure of the initial set selected three branches that could be distributed in three-dimensional space with fewer features. Each branch represented a bundle of fibers, and the bundle of fibers had a cylindrical section, reflecting the relationship between the two bundles. The number of iterations is also selected as two ($n = 2$).