

Virtual Knotting Method of Knotter Based on Rigid-flexible Contact Dynamics

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Abstract: Aiming at the problem of increasing investment cost of knotter production due to difficulty in evaluation of good or bad design after structure improvement or parameters adjustment of the knotter, a kind of virtual knotting method of knotter based on rigid-flexible contact dynamics was presented according to the judgment rule of whether the knotter could tie a knot during design phase. The method used the Bushing connection tool under ADAMS to build up dynamic model of flexible rope with large deformation. A complete virtual knotting simulation process of the knotter was implemented by setting up multiple contact constraint between the rope and rigid component of the knotter and applying load to the rope. Rigid-flexible interactive mechanical behaviors of tying a knot of the knotter were studied under the action of pulling force of the rope. The comparison analyses between knotting movements of the knotter prototype and virtual knotting results validated the correctness of dynamic model of the rope and simulation model of rigid-flexible contact dynamics. It may be regarded as an effective method to evaluate good or bad design and guarantee disposable successful production of the knotter. The effects of the timing sequence difference value φ between the motion of knotting hook and the motion of rope-holding plate on knotting motion of the knotter were analyzed by using the proposed virtual knotting method, which can play visual validation role to judge whether the knotter can knot or tie a good and bad knot after parameters match of the knotter.

Key words: baler; knotter; contact dynamics; virtual knotting; ADAMS

0 Introduction

D-knotter is the core component of the square bundle baler. However, the production of square bundle baler always relies on imported D-knotter in China. To simplify the structure of the knotter, the structure or parameters of the knotter were adjusted^[1-3]. Generally, trial produce stage of knotter prototype started after kinematic analysis combined with virtual assembly was finished. However, whether the improved knotter can tie a knot is a lack of visual methods to judge the advantages and disadvantages of the design, which may lead to failure of the trial manufacture and increase the risk of manufacturing investment. Therefore, it is necessary that the method of virtual knotting was studied to improve the design theory of the knotter.

Compared with the rigid motion simulation of knotter^[4-6], the study on dynamics of rigid-flexible

contact in the process of knotting is more complex due to the difference of the mechanical properties and flexible large deformation of the rope. In foreign countries, the representative research is that numerical simulation based on proton-spring model was established to develop the motion process of underwater fishing net^[7-8]. However, Chinese researchers have usually used commercial software to simulate the complex process of rope movement. For example, Dynamic simulation modeling method for complex rope was built based on seat belt unit under the software of LS-DYNA, and node-surface contact model was used to realize contact simulation between flexible net body and object^[9]. Joint simulation of dental arch curve generator was conducted under the environment of both ANSYS and ADAMS^[10]. Simulation of rope-knotting was achieved in virtual surgery environment^[11]. The above researches provide some ideas and effective way for studying on virtual knotting method of D-Knotter

based on rigid-flexible contact dynamics.

In this paper, in view of the problem of increasing investment cost of knotter production due to be difficult to evaluate good or bad design during design phase after structure improvement or parameters adjustment of the knotter, the Bushing connection model under ADAMS is used to build up dynamic model of flexible rope with mechanical properties. According to the judgment rule of whether the knotter could tie a knot, a kind of virtual knotting method of knotter is presented to study on rigid-flexible interactive mechanical behaviors of tying a knot of the knotter under the action of pulling force of the rope in order to provide an effective method to evaluate good or bad design and guarantee disposable successful production of the knotter.

1 Dynamic model of rope

The rope is a flexible body with large deformation, and the modality is adopted to represent the elasticity of the object. Compared with large deformation of rope-knotting, elastic deformation of the rope is smaller. Assumed that the rope is composed of a number of micro cylinders, each micro segment may be treated as a rigid body. Adjacent micro cylinders are connected by Bushing force under the environment of ADAMS. The combination of all micro segments can be regarded as a flexible body model of rope because tiny length of micro cylinder is far less than the total length of rope. The Bushing force is applied to two micro segments of the cylinder to make them interact with each other. The connection model of flexible force is obtained by three components of force and three components of torque $(F_x, F_y, F_z, T_x, T_y, T_z)$ at the center of connecting position of the two cylinders, as shown in Fig. 1.

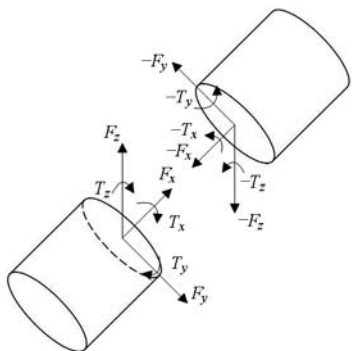


Fig.1 Dynamic model of the rope based on Bushing connection

The Bushing force can be expressed as the following matrix (Eq. (1)) according to the mechanics theory^[12].

$$\begin{bmatrix} F_x \\ F_y \\ F_z \\ T_x \\ T_y \\ T_z \end{bmatrix} = \mathbf{K} \begin{bmatrix} r_x \\ r_y \\ r_z \\ \theta_x \\ \theta_y \\ \theta_z \end{bmatrix} - \mathbf{C} \begin{bmatrix} v_x \\ v_y \\ v_z \\ \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} + \begin{bmatrix} F_{x0} \\ F_{y0} \\ F_{z0} \\ T_{x0} \\ T_{y0} \\ T_{z0} \end{bmatrix} \quad (1)$$

Here, $\mathbf{K}$ is a 6×6 diagonal matrix of stiffness coefficient of the rope, and $\mathbf{C}$ is a 6×6 diagonal matrix of damping coefficient of the rope. (F_{x0}, F_{y0}, F_{z0}) is initial value of component force along the direction of coordinate axis. (T_{x0}, T_{y0}, T_{z0}) is initial value of component torque along the direction of coordinate axis. (r_x, r_y, r_z) , $(\theta_x, \theta_y, \theta_z)$, (v_x, v_y, v_z) and $(\omega_x, \omega_y, \omega_z)$ are displacement, rotor angle, velocity and angular velocity of coordinate system at the center of the first micro cylinder relative to coordinate system at the center of the second micro cylinder, and they are automatically determined by solver of ADAMS.

Computed expressions of diagonal elements of stiffness coefficient matrix of the rope are respectively

$$K_{11} = \frac{EA}{L} \quad K_{22} = K_{33} = \frac{GA}{L}$$

$$K_{44} = \frac{2GI}{L} \quad K_{55} = K_{66} = \frac{EI}{L}$$

Here, K_{11} is tensile stiffness coefficient, and K_{22} and K_{33} are shear stiffness coefficients. K_{44} is coefficient of torsional rigidity, and K_{55} and K_{66} are coefficients of bending rigidity. A is sectional area of the rope, and L is length of the rope. E is elasticity modulus of the rope. G is shear modulus of the rope, and may be calculated by

$$G = \frac{E}{2(1 + \mu)}$$

Where, μ is Poisson ratio.

I is central moment of inertia of the rope, and expressed as

$$I = \frac{\pi}{64} D^4$$

Where, D is diameter of the rope.

Viewed from Eq. (1), the flexible force value between two micro cylinders is related to material properties of the rope, their relative displacement, rotation angle, velocity and angular velocity. Here, a

polypropylene rope with the diameter of 2.5 mm and the length of 480 mm is chosen. According to mechanical properties of polypropylene^[13], the value of E is 1.32 GPa, and the value of μ is chosen as 0.35. We can figured out the following datum, and wrote as

$$\begin{aligned} G &= 0.49 \text{ GPa} \\ I &= 1.92 \text{ mm}^4 \\ K_{11} &= 13\,502.5 \text{ N/m} \\ K_{22} = K_{33} &= 5\,012.3 \text{ N/m} \\ K_{44} &= 3\,920.0 \text{ N/m} \\ K_{55} = K_{66} &= 5\,280.0 \text{ N/m} \end{aligned}$$

According to creep properties of polypropylene^[13], diagonal elements of damping coefficient matrix C may be determined as

$$\begin{aligned} C_{11} = C_{22} = C_{33} &= 0.71 \text{ N}\cdot\text{s/m} \\ C_{44} = C_{55} = C_{66} &= 0.1 \text{ N}\cdot\text{s/m} \end{aligned}$$

According to above parameters, the stiffness and damping coefficient of the rope model between adjacent two micro segments are set up under ADAMS to make mechanical properties of the whole rope model approximate to real rope, and the deformation and dynamic performance of the whole rope may be simulated.

2 Knotter modeling based on rigid-flexible contact dynamics

2.1 Virtual prototype model of knotting device of knotter

The virtual prototype model of knotting device was created under the environment of SolidWorks software,

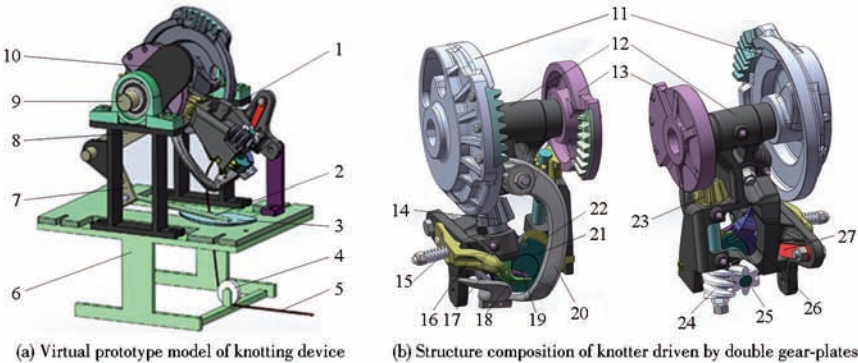


Fig.2 Virtual prototyping model of knotting device of knotter

1. Knotter driven by double gear-plates 2. Connecting rod 3. Rope-guiding plate 4. Pulley 5. Rope 6. Knotter stand 7. Rope-guiding crack 8. Swing rod 9. Drive spindle 10. Rope-guiding cam 11. Big gear disc 12. Knotter stand 13. Small gear disc 14. Bevel gear installed on knotting hook 15. Pressure spring 16. Platen 17. Rope-cutting knife 18. Knotting hook 19. Biting hook 20. Knife arm 21. Rope-holding plate 22. Static slice of rope-holding 23. Bevel gear installed on worm axle 24. Worm 25. Helical gears 26. Moving slice of rope-holding 27. Rope-holding platen

as shown in Fig. 2a. Considering the rope is forced to be affixed to the surface of knotting hook by rope-guiding plate, the rope-guiding mechanism model was also established in the virtual prototype model of knotting device. Rope-guiding mechanism is mainly made up of cam mechanism and spatial crank rocker mechanism in series, and makes the rope lap on the surface of knotting hook. D-knotter driven by double gear-discs was used in the model of knotting device, as shown in Fig. 2b. The assembly model of knotter was saved as format of *.x_t file under the environment of SolidWorks software, and the file was imported into ADAMS. The quality characteristics of the imported model need to be modified to fit in with actual material. In addition, some unnecessary parts were deleted under ADAMS to simplify simulation model of knotting device.

To validate whether the knotter driven by double gear discs can knot, the rope model is built in the virtual prototype model, as shown in Fig. 2a. 240 small cylinders with diameter of 2.5 mm and length of 2 mm were connected to build up a whole rope by with Bushing force. According to rope shape after rope-sending motion of rope needle, one end of rope lapped on the notch of rope-holding plate, and another end of rope was set up to contact with pulley.

2.2 Simulation model setup of knotting device of knotter

2.2.1 Setup of drive and constraint

Rotary drive of 540°/s is applied to the drive principal axis of knotter according to rated rotation speed of 90 r/min. According to the actual connection

relationship between the components of the knotting device, all constraints need to be added under the environment of ADAMS, as shown in Tab.1. The relationship of contact was set up to “solid to solid” type of connection for bevel gear transmission, worm transmission, rope and other rigid components. Bushing force was added among 240 small cylinders, which is divided into two parts of translation and rotation. According to the dynamic model of rope, the value of K_{11} , K_{22} , K_{33} , C_{11} , C_{22} and C_{33} may be set to translation motion, and the value of K_{44} , K_{55} , K_{66} , C_{44} , C_{55} and C_{66} may be set to rotation motion.

Tab.1 Constraint relation configuration among components

Number of components		Type of constraint
6	Ground	Fixed joint
6	12	Fixed joint
10,11,13	7	Fixed joint
10	8	Contact
7	2	Spherical joint
2	3	Spherical joint
3	6	Revolute joint
6	9	Revolute joint
14	11	Contact
12	18	Revolute joint
11	23	Revolute joint
24	12	Revolute joint
24	25	Contact
20,21	12	Revolute joint
8,18,19,20,21,26	5	Contact
5	5	Bushing

Numerical iterative method was generally adopted to solve dynamic equations that are made up of differential-algebraic equations in ADAMS for virtual prototype model of multi-contact constraint machine system^[15]. According to judgment rule of contact and contact dynamics model, contact force will be merged into generalized force matrix when ADAMS solver computes the dynamics equations. Different contact surfaces and contact type may be defined for different components. Therefore, contact constraints among rope and knotter components are added to avoid penetration phenomenon between rope model and D-knotter. It is necessary to modify dynamic friction coefficient and static friction factor of components that were set up contact constraints. Dynamic friction coefficient between rope and knotting hook, biting hook, rope-holding plate, knife arm were set to 0.18, and their static friction coefficients were set to 0.37^[16]. The

contact constraints of microcylinders were also added to avoid penetration phenomenon among micro cylinders during knotting because penetration phenomenon will lead to knotting failure. In order to improve computational efficiency of ADAMS solver, contact constraints were only added to some micro cylinders which exist contact relationship each other in the rope model.

2.2.2 Applied load

As shown in Fig. 3, the change process of the rope force may be measured by using knotting test bench, the measurement way is as following:

Two tension sensors are connected with primary and secondary rope respectively, and the pulling force is recorded in the process of knotting by manually driving the flywheel to rotate the spindle of the knotter, as shown in Fig.4.

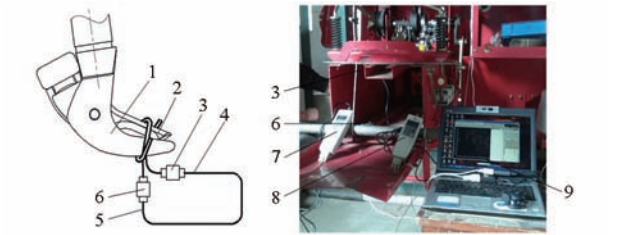


Fig.3 Pulling force measurement and principle of rope
1. Knotting hook 2. Biting hook 3. Tension sensor of primary rope 4. Primary rope 5. Secondary rope 6. Tension sensor of secondary rope 7. Monitor of tension sensor of secondary rope 8. Monitor of tensionsensor of primary rope 9. Computer system of pulling force collection

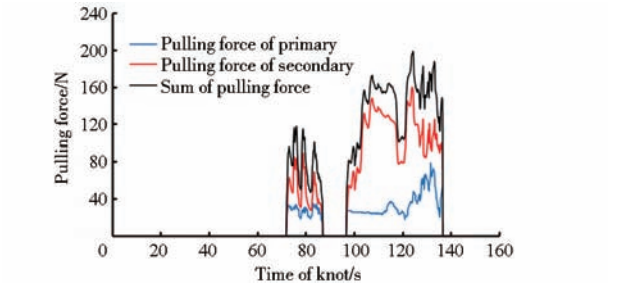


Fig.4 Pulling force curve of the rope

Single rope is used in virtual knotting, and there are double ropes during actual knotting. The peak value of pulling force sum between primary rope and secondary rope is chosen to simulate the actual force of the rope. As shown in Fig. 4, the peak value of the pulling force is 200 N. Therefore, the pulling force of the rope is added among normal direction at the end of the rope model, which value is set up to 200 N. Another pulling force driven by STEP function is added at the rope end of rope-holding plate to simulate the condition of rope-

cutting after the knot finishes. STEP function is expressed as following:

$$F = \text{STEP}(\text{time}, 0, 200, 0.48, 200) + \text{STEP}(\text{time}, 0.48, 0, 0.5, -200)$$

The meaning of setting the force is that the pulling force at the end of rope model will disappear when the knife contacts with rope between knotting hook and rope-holding plate, which can approximately simulate actual situation of rope-cutting. When the time is set to 0.5 s, knife contacts with rope between knotting hook and rope-holding plate after simulations is tried to finish several times. For Eq. (1), the initial value of F_{x0} , F_{y0} and F_{z0} were set to 200 N, 0 N and 0 N respectively. The initial value of T_{x0} , T_{y0} and T_{z0} were also set to 0 N·m, 0 N·m and 0 N·m respectively.

3 Virtual knotting and experiment validation of knotter

3.1 Virtual knotting simulation

Virtual prototype simulation of the knotting device can be executed by ADAMS solver after above drive, constraints and load were set up, as shown in Fig.5.

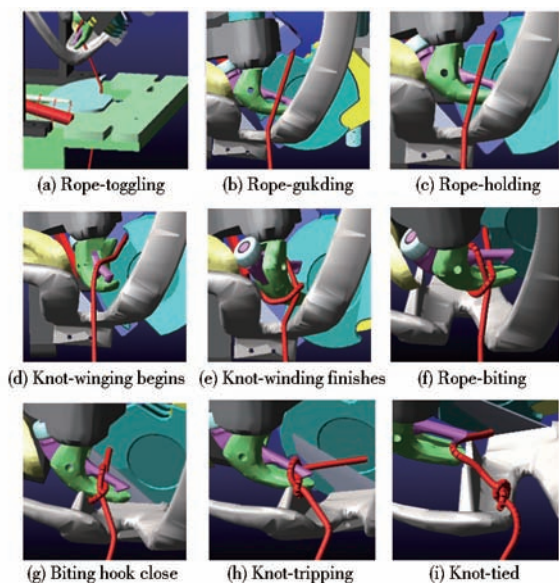


Fig.5 Knotting simulation process drawing of knotter driven by double gear-discs

To decrease the calculated amount and difficulty of simulation, single rope is used in virtual knotting, and double ropes are applied into actual knotting. But it has no effect on validity and correctness of virtual knotting.

Viewed from the knotting simulation processes shown in Fig.5a to Fig.5i, multi-contact constraints of virtual prototype of the knotting device were set up rightly,

and dynamics modeling method of the rope is feasible and parameters setup of the rope is right. The virtual knotting may simulate large deformation and dynamic behavior of the rope, and can reproduce the process of the contact constraint between the rope and the rigid member under the action of tension. Rigid-flexible interaction process of forming a knot may be real-time observed under the action of tension by the virtual knotting, including dynamic process of forcing the rope to lap on the surface of knotting hook by rope-guiding plate, guiding the rope into the arc notch of knife arm by arc surface of knife arm, holding and rotating the rope by rope-holder, twisting the rope into a ring by knotting hook, opening biting hook and clamping the rope, closing biting hook and pulling out the rope head, and forcing rope ring twined on the surface of knotting hook to break off by knife arm. For the rope model in literature [4], stiffness coefficient of the rope was only considered and set to fixed value. At the same time, damping coefficient matrix of the rope was ignored. The dynamic model of rope established in this paper is close to actual mechanical properties of the rope, and may accurately describe large deformation and dynamic performance of whole rope.

During virtual knotting, if the rope end located at rope-holding plate is fixed and another end of the rope is applied normal pulling force along end surface of the rope, the simulation results were shown in Fig. 6, which is different from actual knotting process. The reason is that it is difficult for ADAMS solver to simulate the process of cutting off the rope by knife installed on knife arm. One end of the rope is clamped by rope-holder, and rope ring twined on the surface of knotting hook can't be broken off by knife arm and rolls back to the surface of biting hook around knotting hook until rope ring disperses, which leads to failure of virtual knotting simulation. It is the reason that pulling force driven by STEP function was added to the end of rope located at rope-holding plate. In literature [4], motion of cutting off rope was simulated approximately by controlling motion of micro cylinders based on secondary development of ADAMS, and high requirement is needed to secondary development of ADAMS. For motion simulation of cutting off rope, the method of cutting off rope mentioned in this paper is more universal and easier to come true.

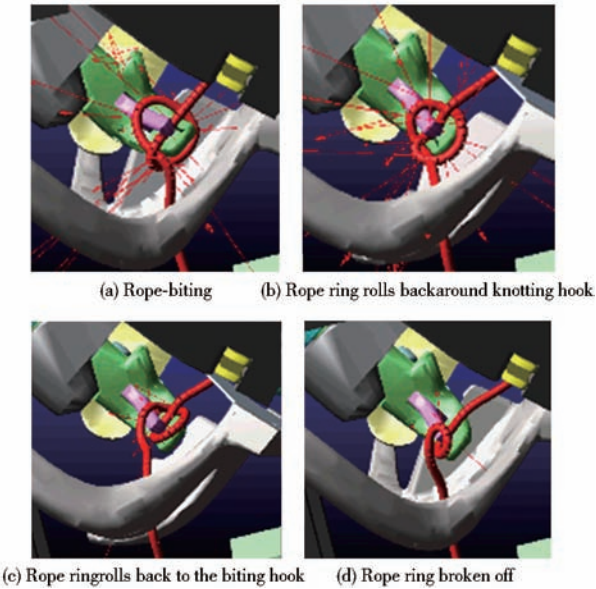


Fig. 6 Problem of cutting rope motion of virtual knotting

3.2 Experimental validation of virtual knotting

The designed knotter driven by double gear-disc was installed in indoor knotting platform, tensile force of rope, pressure value of compression spring of biting hook and rope-holding plate were adjusted appropriately. The knotter was driven slowly to do knotting motion under the condition of no straws. In comparison with virtual knotting, digital camera was used to record the process of tying a knot, as shown in Fig. 7. Left side view is virtual knotting, and right side view is actual knotting of knotter prototype.

Viewed from Fig. 7a to Fig. 7g, virtual knotting is fit remarkably well with actual knotting of knotter prototype. The result shown that virtual knotting method may be applied into verifying knotting effect of the knotter after structure improvement or parameters adjustment of the knotter during design stage, and guarantee disposable successful production of the knotter and decrease greatly investment cost.

3.3 Application of virtual knotting

The timing difference φ between the knotting hook and rope-holding plate and intersection angle α between the knotting hook shaft and principal axis of knotter are two basic parameters of knotter design^[1]. By using above virtual knotting method, value of α and φ may be adjusted to verify correctness of the two parameters matching. Here, the value of φ is 98° and the value of α is chosen as 2.5° , 7.5° , 12.5° , 17.5° and 22.5° respectively. In the Fig. 8, the installation phase difference ψ between bevel gear installed on

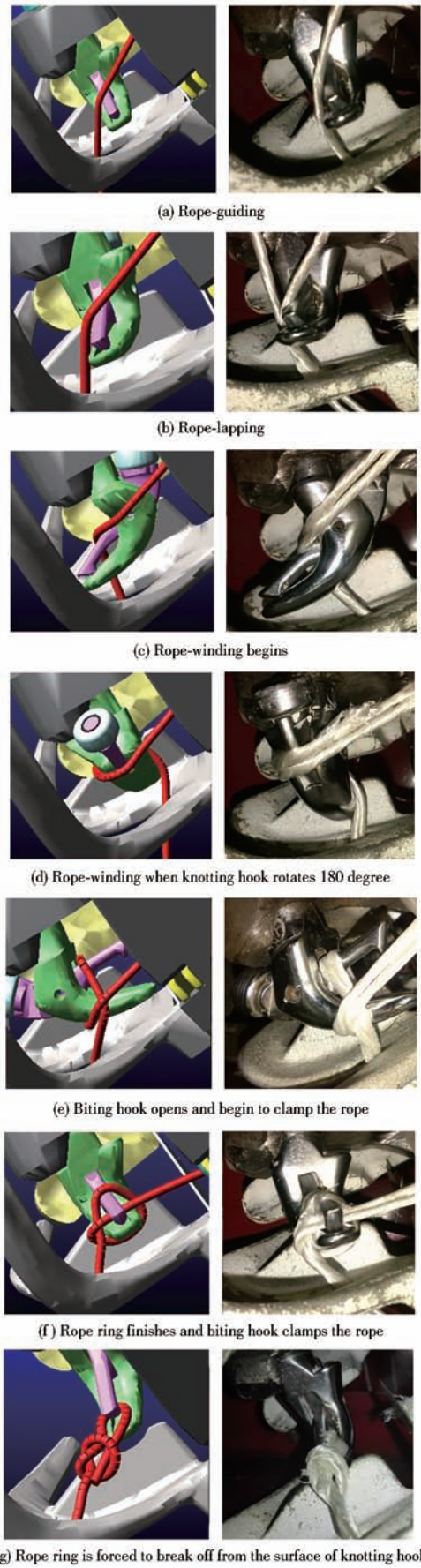


Fig. 7 Contrast of knotting process between virtual prototype and knotter prototype

worm axle and bevel gears installed on knotting hook is

30°. The installation phase difference ε between incomplete bevel gears installed on the small gear disc and big gear disc respectively may be calculated by ^[14]

$$\varepsilon = \varphi + \psi$$

Thus, the value of ε is 32.5°, 37.5°, 42.5°, 47.5° and 52.5°.

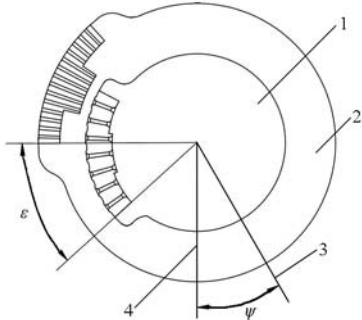


Fig. 8 Installation phase difference between bevel gears on the gear-discs

- 1. Small gear disc 2. Big gear disc 3. Knotting hook axis 4. Worm axle axis

Virtual prototypes of knotter were modified to make the ε of 32.5°, 37.5°, 42.5°, 47.5° and 52.5° respectively, and each virtual knotting was carried out and compared with the virtual knotting when the value of φ was 12.5°, as shown in Fig. 9 to Fig. 13.

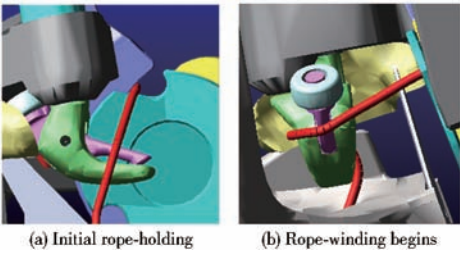


Fig. 9 Virtual knotting when φ was 2.5°

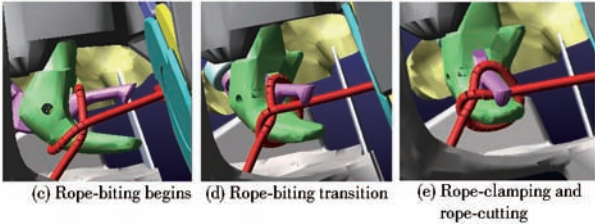
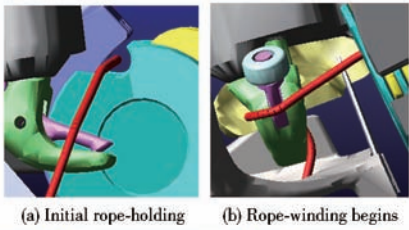


Fig. 10 Virtual knotting when φ is 7.5°

Viewed from Fig. 9a to Fig. 13a, when the value of φ varies from 2.5° to 22.5°, relative rotation of rope-holding plate is earlier gradually than knotting hook

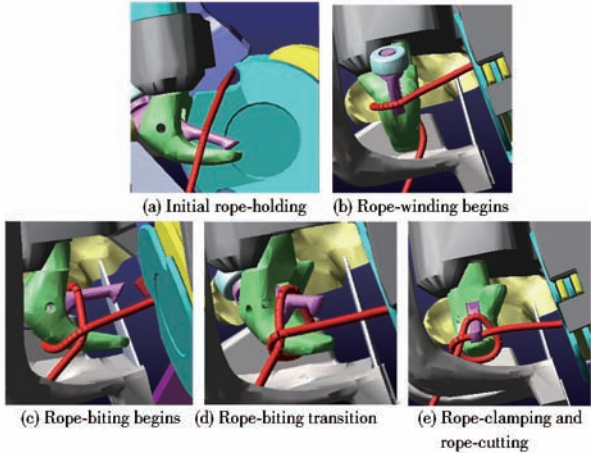


Fig. 11 Virtual knotting when φ is 12.5°

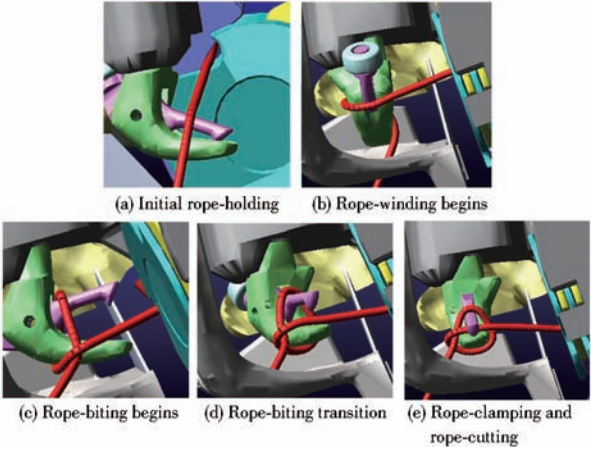


Fig. 12 Virtual knotting when φ is 17.5°

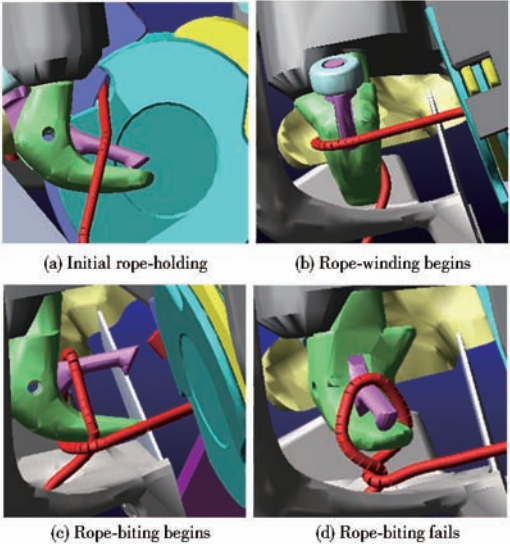


Fig. 13 Virtual knotting when φ is 22.5°

with the beginning of rope-winding. Clamping point of the rope deviated towards the moving slice of rope-holding along anticlockwise rotation direction of rope-holding plate when the φ increases gradually, and locates gradually at the close space formed between rope-holding plate and the moving slice of rope-holding.

When the φ is 2.5° , the rope-holding plate doesn't force the rope into the moving slice of rope-holding with the beginning of rope-winding. The rope is brought back by rope needle after rope-winding starts and virtual knotting fails, which indicates that incomplete bevel gears transmission between small gear disc and worm axle meshes and lags behind incomplete bevel gears transmission between big gear disc and knotting hook axle. That is, 2.5° value of the φ is too smaller.

When the φ is 7.5° , the rope doesn't be completely sent into the moving slice of rope-holding by rope-holding plate. However, under the auxiliary action of rope needle, the rope is able to be clamped with rotation of knotting hook, which has no effect on virtual knotting.

When the φ is 12.5° , the rope is completely sent into the moving slice of rope-holding by rope-holding plate and clamped between the moving slice of rope-holding and rope-holding plate. When the φ is 17.5° and 22.5° , the rope has been clamped between the moving slice of rope-holding and rope-holding plate before rope-winding motion begins.

Viewed from Fig. 10c to Fig. 10d, when the φ is 7.5° , the rope locates at the upper position of the midpoint of the end line between knotting hook and biting hook, and close to biting hook. The rope may be clamped by biting hook.

Viewed from Fig. 12c to Fig. 12e, when the φ is 17.5° , the rope locates at the lower position of the midpoint of the end line between knotting hook and biting hook, and close to the surface of knotting hook. The rope may also be clamped by biting hook.

Viewed from Fig. 11c to Fig. 11e, when the φ is 17.5° , the rope locates at the midpoint of the end line between knotting hook and biting hook and the rope may reliably be clamped by biting hook, which indicates that an ideal position of biting the rope may be obtained.

Viewed from Fig. 13c to Fig. 13d, when the φ is 22.5° , the clamping point of the rope on the rope-holding plate is too low to clamp the rope by biting hook because the rope slides to the side of knotting hook. The failure of biting the rope leads to the failure of knotting. That is, 22.5° value of the φ is too bigger.

Viewed from above analyses, virtual knotting may be accomplished when the value of α is 98° and the value of φ varies from 7.5° to 17.5° , which indicates that the installation phase difference ε is allowed to adjust from 37.5° to 47.5° and the error of the ε is about angle of half tooth of bevel gear.

Viewed from Fig. 9 to Fig. 13, the effect of virtual knotting may be observed clearly when the value of φ varies, and is more intuitive than the results of numerical simulation after analytic calculation. Virtual knotting may play an intuitive validation role to judge whether parameters matching of knotter fit, and contributes to form new knotter design scheme.

The problem of being hard to validate intuitively knotting effect after the knotter design may be solved by using the virtual knotting. The design defects may be found during design stage of knotter, and investment cost of knotter manufacture may be greatly decreased.

4 Conclusions

(1) Acomplete realization method of virtual knotting based on rigid-flexible contact dynamics was established. By comparing knotting motion of knotter prototype with simulation results of virtual knotting, the correctness of dynamics model of the rope and rigid-flexible contact dynamics simulation of the knotter are validated. The virtual knotting may be regarded as an effective method to evaluate good or bad design and guarantee disposable successful production of the knotter.

(2) By rigid-flexible contact dynamics simulation of the knotting processes of knotter driven by double gear plates, bushing force connection under ADAMS is able to solve establishment and simulation problem of flexible body model with large deformation, and has the reference value to design and analysis of mechanism with rigid-flexible contact.

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基于刚柔接触动力学的打结器虚拟打结方法研究

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摘要: 针对打结器结构改进或参数调整后在设计阶段难以评判优劣而增加制造投入成本的问题,以打结器能否打出绳结为评判准则,提出了一种基于刚柔接触动力学的打结器虚拟打结方法。该方法利用 ADAMS 的 Bushing 连接建立大变形柔性捆绳的动力学模型,通过对捆绳和刚性构件之间设置多接触约束和载荷施加,实现了完整的打结器虚拟打结仿真过程,研究了捆绳在拉力作用下成结的刚柔交互力学行为。通过对打结器样机的成结动作与虚拟打结的仿真结果进行对比分析,验证了捆绳动力学模型与刚柔接触动力学仿真模型的正确性,可作为评价设计优劣、保证打结器一次性制造成功的有效方法。利用该虚拟打结方法分析了打结嘴与夹绳盘动作时序差 φ 对打结器成结的影响,对判定打结器参数匹配后能否成结或成结优劣起到了直观验证作用。

关键词: 打捆机; 打结器; 接触动力学; 虚拟打结; ADAMS

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Virtual Knotting Method of Knotter Based on Rigid-flexible Contact Dynamics

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Abstract: Aiming at the problem of increasing investment cost of knotter production due to difficulty in evaluation of good or bad design after structure improvement or parameters adjustment of the knotter, a kind of virtual knotting method of knotter based on rigid-flexible contact dynamics was presented according to the judgment rule of whether the knotter could tie a knot during design phase. The method used the Bushing connection tool under ADAMS to build up dynamic model of flexible rope with large deformation. A complete virtual knotting simulation process of the knotter was implemented by setting up multiple contact constraint between the rope and rigid component of the knotter and applying load to the rope. Rigid-flexible interactive mechanical behaviors of tying a knot of the knotter were studied under the action of pulling force of the rope. The comparison analyses between knotting movements of the knotter prototype and virtual knotting results validated the correctness of dynamic model of the rope and simulation model of rigid-flexible contact dynamics. It may be regarded as an effective method to evaluate good or bad design and guarantee disposable successful production of the knotter. The effects of the timing sequence difference value φ between the motion of knotting hook and the motion of rope-holding plate on knotting motion of the knotter were analyzed by using the proposed virtual knotting method, which can play visual validation role to judge whether the knotter can knot or tie a good and bad knot after parameters match of the knotter.

Key words: baler; knotter; contact dynamics; virtual knotting; ADAMS

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引言

D 型打结器是方捆机捆扎装置的核心部件,但我国方捆机的生产长期依赖进口打结器。为了简化打结器结构,对打结器进行结构改进或参数调整^[1-3],一般采用运动分析结合虚拟装配后即进入样机试制阶段,但改进后的打结器能否打出理想绳结,缺乏直观可视化的实现方法来验证设计优劣,未经虚拟打结验证设计优劣的打结器试制,可能导致试制失败而使制造投入面临风险。因此,有必要研究打结器虚拟打结实现方法来完善打结器设计理论。

与打结器刚性执行机构的动作仿真^[4-6]相比,由于捆绳的力学特性差异和柔性大变形问题,对打结过程的刚柔接触动力学研究十分困难。国外对绳索类动力学研究主要基于质子-弹簧模型对水下渔网运动过程进行了数值模拟^[7-8]。国内较多采用商用软件对复杂绳索体运动过程进行模拟,比如:文献[9]采用 LS-DYNA 安全带单元研究复杂绳索体动力学仿真建模方法,采用“节点-表面”接触类型实现柔性网体与对象的接触模拟。文献[10]采用 ANSYS 和 ADAMS 软件对多操作机排牙机器人系统中的牙弓曲线发生器进行联合仿真。文献[11]研究了虚拟手术中绳子打结的仿真实现。上述研究方法为打结器刚柔接触动力学行为研究提供了思路和有效途径。

本文针对打结器结构改进或参数调整后在设计阶段难以评判优劣而增加制造投入风险的问题,基于 ADAMS 的 Bushing 模型建立反映捆绳柔性和力学特性的动力学模型,以打结器能否打出绳结为评判准则,提出打结器虚拟打结的实现方法,研究捆绳在拉力作用下打结过程的刚柔交互力学行为,为打结器一次性制造成功提供评价设计优劣的有效方法。

1 捆绳动力学模型

捆绳为大变形柔性体,而柔性体采用模态来表示物体的弹性,相对捆绳打结的大变形而言,捆绳的弹性是小变形。假设捆绳由若干微段圆柱组成,每个微段均视作刚体,相邻两个微段圆柱通过 ADAMS 软件中的 Bushing 力连接,当微段圆柱相比捆绳总长度很小时,该微段刚体组合模型可视为捆绳的柔性体模型。在两微段圆柱间施加 Bushing 力并使其相互作用,通过在两微段圆柱中心连接处定义沿坐标系轴的 3 个分力和 3 个分力矩(F_x 、 F_y 、 F_z 、 T_x 、 T_y 、 T_z)获得柔性力连接受力模型,如图 1 所示。

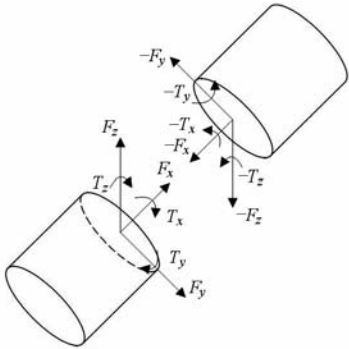


图 1 基于 Bushing 力连接的捆绳动力学模型
Fig. 1 Dynamic model of the rope based on Bushing connection

根据力学理论,Bushing 力^[12]可表示为

$$\begin{bmatrix} F_x \\ F_y \\ F_z \\ T_x \\ T_y \\ T_z \end{bmatrix} = K \begin{bmatrix} r_x \\ r_y \\ r_z \\ \theta_x \\ \theta_y \\ \theta_z \end{bmatrix} - C \begin{bmatrix} v_x \\ v_y \\ v_z \\ \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} + \begin{bmatrix} F_{x0} \\ F_{y0} \\ F_{z0} \\ T_{x0} \\ T_{y0} \\ T_{z0} \end{bmatrix} \quad (1)$$

- 式中 K ——捆绳刚度矩阵,为 6×6 对角矩阵
 C ——捆绳阻尼系数矩阵,为 6×6 对角矩阵
(F_{x0}, F_{y0}, F_{z0})——沿坐标轴方向分力初始值
(T_{x0}, T_{y0}, T_{z0})——沿坐标轴方向分力矩初始值
(r_x, r_y, r_z)——第 1 微段圆柱中心处坐标系相对于第 2 微段圆柱中心处坐标系的相对位移
($\theta_x, \theta_y, \theta_z$)——第 1 微段圆柱中心处坐标系相对于第 2 微段圆柱中心处坐标系的转角
(v_x, v_y, v_z)——第 1 微段圆柱中心处坐标系相对于第 2 微段圆柱中心处坐标系的速度
($\omega_x, \omega_y, \omega_z$)——第 1 微段圆柱中心处坐标系相对于第 2 微段圆柱中心处坐标系的角速度
(r_x, r_y, r_z)、($\theta_x, \theta_y, \theta_z$)、(v_x, v_y, v_z)、($\omega_x, \omega_y, \omega_z$)由求解器自动确定。

捆绳刚度矩阵对角元素计算式为

$$K_{11} = \frac{EA}{L} \quad K_{22} = K_{33} = \frac{GA}{L} \quad K_{44} = \frac{2GI}{L}$$
$$K_{55} = K_{66} = \frac{EI}{L} \quad G = \frac{E}{2(1+\mu)} \quad I = \frac{\pi}{64} D^4$$

- 式中 K_{11} ——拉伸刚度
 K_{22} 、 K_{33} ——剪切刚度
 K_{44} ——扭转刚度
 K_{55} 、 K_{66} ——弯曲刚度

E ——捆绳弹性模量
 G ——捆绳剪切模量 μ ——泊松比
 I ——捆绳中心惯性矩
 $A、D、L$ ——捆绳截面积、直径和长度

由式(1)可看出,相邻两微段圆柱间的柔性力大小与捆绳材料特性、相对位移、转角、速度、角速度有关。在此,捆绳选直径 $D = 2.5\text{ mm}$ 的聚丙烯绳,长度 $L = 0.48\text{ m}$ 。根据聚丙烯的力学特性^[13], $E = 1.32\text{ GPa}$, $\mu = 0.35$, 经计算得出 $G = 0.49\text{ GPa}$, $I = 1.92\text{ mm}^4$, $K_{11} = 13\,502.5\text{ N/m}$, $K_{22} = K_{33} = 5\,012.3\text{ N/m}$, $K_{44} = 3\,920.0\text{ N/m}$, $K_{55} = K_{66} = 5\,280.0\text{ N/m}$ 。根据聚丙烯的蠕变特性^[13], 阻尼系数矩阵 C 的对角线元素 $C_{11} = C_{22} = C_{33} = 0.71\text{ N}\cdot\text{s/m}$, $C_{44} = C_{55} = C_{66} = 0.1\text{ N}\cdot\text{s/m}$ 。

按上述参数在 ADAMS 中设定相邻两微段捆绳模型的刚度及阻尼系数,使整段捆绳模型的力学性能接近捆绳真实力学性能,从而可模拟整段捆绳的

变形及动力学性能。

2 打结器刚柔接触动力学建模

2.1 打结器成结装置的虚拟样机模型

采用 SolidWorks 软件建立打结器成结装置模型,如图 2a 所示。考虑到打结过程中拨绳盘的拨绳动作迫使捆绳搭接在打结嘴上,故将拨绳机构一并建立到虚拟打结模型中。拨绳机构由拨绳凸轮机构与空间曲柄摇杆机构串联而成,其功能是拨绳盘将捆绳拨向打结嘴使捆绳搭接在打结嘴表面上,为打结嘴绕扣做准备。成结装置模型中采用双齿盘驱动打结器^[14],其结构组成如图 2b 所示。将 SolidWorks 软件下的打结器成结装置模型转换成 parasolid 图形核心的 *.x_t 格式,再将该中间文件导入到 ADAMS 软件中,对导入的模型修改质量特性以保持与实际材料特性相符,并删除局部不影响仿真分析的零件,以简化仿真模型。

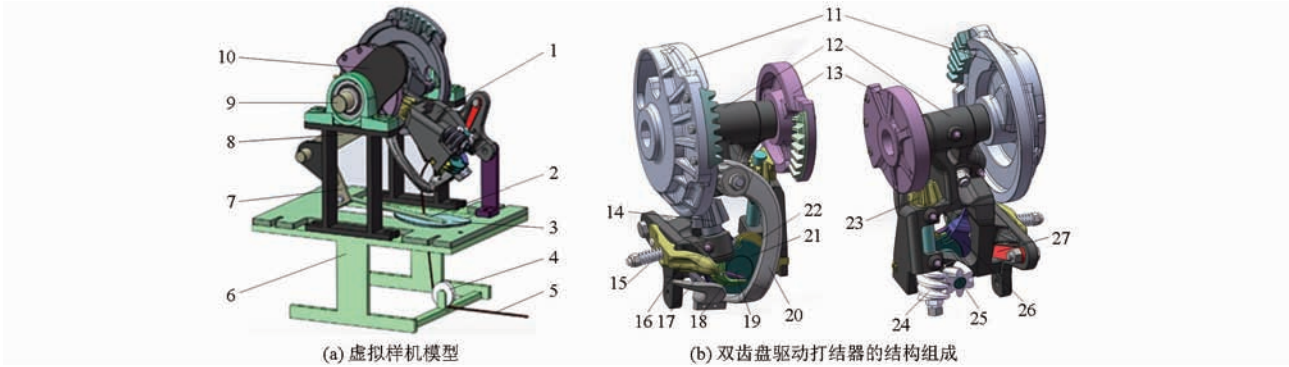


图 2 打结器成结装置虚拟样机模型

Fig. 2 Virtual prototyping model of knotting device of knotter

1. 双齿盘驱动打结器 2. 连杆 3. 拨绳盘 4. 滚轮 5. 捆绳 6. 机架 7. 拨绳曲柄 8. 摆杆 9. 驱动主轴 10. 拨绳凸轮 11. 大齿盘
12. 打结器支架 13. 小齿盘 14. 打结嘴锥齿轮 15. 压簧 16. 压板 17. 割绳刀 18. 打结嘴 19. 钩钳 20. 刀臂 21. 夹绳盘 22. 夹绳静片 23. 蜗杆轴锥齿轮 24. 蜗杆 25. 斜齿轮 26. 夹绳动片 27. 夹绳压板

为了检验设计的双齿盘驱动打结器是否可以实现捆绳打结,在图 2 所示的虚拟样机模型中建立捆绳模型。在此,采用 240 个直径 2.5 mm、长度 2 mm 的小圆柱体通过 Bushing 力相互连接起来形成整根捆绳,按照送绳结束之后捆绳的形态进行装配,即捆绳一端搭接在夹绳盘槽口,捆绳另一端与滑轮形成接触。

2.2 打结器成结装置仿真模型设置

2.2.1 驱动及约束设置

打结器驱动主轴的额定转速为 90 r/min,故对驱动主轴施加旋转驱动为 540°/s。根据打结器成结装置构件之间的实际连接关系在 ADAMS 下添加相应的运动副,如表 1 所示。对于锥齿轮传动和蜗杆传动、捆绳和刚性构件均存在接触关系,将其运动副均设置为“solid to solid”接触连接。捆绳的 240 个小

圆柱之间均添加 Bushing 力连接,Bushing 设置分为两部分,平移运动部分按捆绳动力学模型中的 K_{11} 、 K_{22} 、 K_{33} 、 C_{11} 、 C_{22} 、 C_{33} 数值进行设定,旋转运动部分按捆绳动力学模型中的 K_{44} 、 K_{55} 、 K_{66} 、 C_{44} 、 C_{55} 、 C_{66} 数值进行设定。

对于多接触约束机械系统的虚拟样机模型,ADAMS 求解器解算一组微分-代数方程构成的动力学方程组^[15],通常采用数值迭代法。根据 ADAMS 采用的接触判断准则和接触动力学模型,求解动力学方程组时,ADAMS 求解器将接触力并入广义力矩阵中求解。对不同构件之间的接触作用,需要通过定义接触表面,设定接触类型来实现。为此,为了避免捆绳与刚性构件之间发生穿透现象,须将捆绳和与打结器中有接触关系的构件之间添加接触副,在本模型中将打结嘴、勾钳、刀臂、夹绳动片、夹绳盘、

表 1 构件之间的约束关系设置

Tab.1 Constraint relation configuration among components

图 2 中构件编号		约束类型
6	大地	固定副
6	12	固定副
10、11、13	7	固定副
10	8	接触副
7	2	球副
2	3	球副
3	6	旋转副
6	9	旋转副
14	11	接触副
12	18	旋转副
11	23	接触副
24	12	旋转副
24	25	接触副
20、21	12	旋转副
8、18、19、20、21、26	5	接触副
5	5	Bushing

拨绳盘与捆绳模型的小圆柱之间添加接触连接。ADAMS 接触连接对话框中提供了接触零件的动摩擦因数和静摩擦因数的参数设置,为了提高仿真的真实性,必须对需要接触的零件的动摩擦因数和静摩擦因数进行设置。由于实际打结中采用聚丙烯绳,添加捆绳与打结嘴、勾钳、夹绳盘、夹绳刀、割绳刀臂的静摩擦因数为 0.37、动摩擦因数为 0.18^[16]。同时,捆绳各段圆柱体之间也须添加接触连接,避免打结过程中各段圆柱之间发生穿透而无法形成绳结。由于有接触关系的各段圆柱之间只占整根捆绳的一小段,故只需将捆绳模型中有接触关系的各段圆柱之间添加接触,可以大大提高 ADAMS 求解器的计算效率。

2.2.2 载荷施加

如图 3 所示,利用室内台架试验测量打结过程中捆绳拉力 F 变化曲线,测量方法如下:

在初级捆绳和次级捆绳上分别串联一个拉力传感器,手动驱动飞轮使打结器主轴转动进行打空结,通过拉力采集计算机系统得到成结过程的捆绳拉力,如图 4 所示。

由于虚拟打结过程是单股绳,而实际打结过程是双股绳。在仿真时取初级捆绳和次级捆绳拉力之和的峰值模拟捆绳的实际受力,由图 4 拉力变化曲线可知该峰值取为 200 N。据此,在捆绳模型末端沿端面法向添加 2 个角度固定、大小为 200 N 的拉力。为了模拟打结器在成结后捆绳被刀臂上的刀片切断的情况,在仿真模型的夹绳盘处捆绳末端添加一个 STEP 函数驱动的拉力,STEP 函数表示如下:

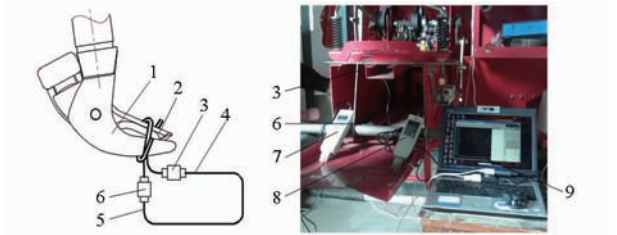


图 3 捆绳拉力原理与测量

Fig.3 Pulling force measurement and principle of rope
1. 打结嘴 2. 钩钳 3. 初级捆绳拉力传感器 4. 初级捆绳
5. 次级捆绳 6. 次级捆绳拉力传感器 7. 次级捆绳拉力传感器显示器 8. 初级捆绳拉力传感器显示器 9. 拉力采集计算机系统

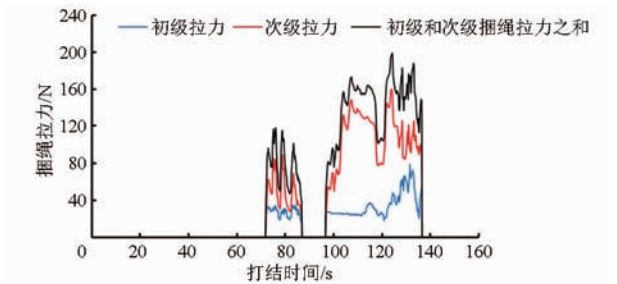


图 4 捆绳拉力变化曲线

Fig.4 Pulling force curves of rope

$$F = \text{STEP}(\text{time}, 0, 200, 0.48, 200) + \text{STEP}(\text{time}, 0.48, 0, 0.5, -200)$$

设置该力的意义是:在割绳刀接触到打结嘴与夹绳盘之间的捆绳时,夹绳盘处捆绳末端拉力消失,可近似模拟捆绳被割绳刀片割断。通过多次仿真尝试设定时间 $t = 0.5 \text{ s}$,割绳刀接触到打结嘴与夹绳盘之间的捆绳。

对式(1)中捆绳各段圆柱之间的分力和分力矩初始值 F_{x0} 、 F_{y0} 、 F_{z0} 、 T_{x0} 、 T_{y0} 、 T_{z0} 分别取为 200 N、0 N、0 N 和 0 N·m、0 N·m、0 N·m。

3 打结器虚拟打结与试验验证

3.1 虚拟打结仿真

经过上述驱动及约束设置和载荷施加后,利用 ADAMS 求解器对打结器成结装置虚拟样机模型进行仿真,其仿真结果如图 5 所示。

为降低仿真计算量和难度,仿真时捆绳为单股,而实际打结是双股,这并不影响虚拟打结的正确性。从图 5a 到图 5i 中的成结仿真过程可见,成结装置的虚拟样机模型中多接触约束设置合适,捆绳的动力学模型建模方法可行,参数设置正确,可以模拟捆绳的大变形及动力学行为,能再现捆绳在拉力作用下与刚性构件之间的接触约束过程。利用虚拟打结可实时观察捆绳在拉力作用下形成绳结的刚柔交互过程,包括拨绳盘将捆绳拨向打结嘴搭接位置的动态过程、捆绳被刀臂的弯曲弧面导入弧形槽口、捆绳

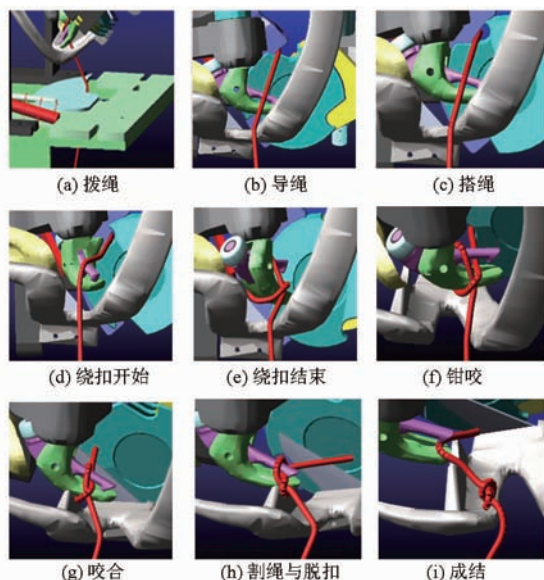


图 5 双齿盘驱动打结器打结仿真过程图

Fig.5 Knotting simulation process drawings of the knotter driven by double gear-discs

被夹绳器夹持旋转、捆绳被打结嘴铰扭成环、钩钳张开钳咬捆绳、钩钳闭合钩出绳头和刀臂强制将绳扣从打结嘴上推脱。对于捆绳模型，文献[4]仅考虑了捆绳刚度系数，且刚度系数矩阵为定值，未考虑捆绳阻尼系数矩阵，而本文建立的捆绳动力学模型接近捆绳真实力学性能，可获得较为准确的整段捆绳的变形及动力学性能。

在虚拟打结仿真中，若夹绳盘处捆绳末端被固定，滚轮侧捆绳末端沿端面法向施加拉力，仿真结果如图 6 所示，这与实际打结过程不符，其原因是 ADAMS 求解器难以仿真捆绳被刀片割断的过程，捆绳一端被夹绳器夹持使得绞扭成环的绳扣缠绕在打结嘴上不能被刀臂强制推脱，而是绳扣绕打结嘴表面反卷到钩钳上，直至绳扣散开，打结仿真失败。这也是在夹绳盘处捆绳末端添加一个 STEP 函数驱动拉力的原因，来近似模拟刀片割绳动作。文献[4]通过 ADAMS 二次开发程序控制微段圆柱运动来近似模拟割绳动作，对 ADAMS 二次开发要求高。而本文模拟割绳动作的方法更具有通用性，便于实现。

3.2 虚拟打结的试验验证

将设计的双齿盘驱动打结器安装到室内打结台架上，试验时调整捆绳张力、钩钳压簧和夹绳压板的压力达到合适值，在不上秸秆物料的情况下，慢速驱动打结器做打结动作，并用数码相机记录打结器成结过程，与虚拟打结仿真结果进行对比，如图 7 所示，其中左侧图为虚拟样机打结，右侧图为打结器样机打结。

由图 7 可见，虚拟打结与打结器物理样机的打结过程非常吻合，表明该虚拟打结实现方法可以用

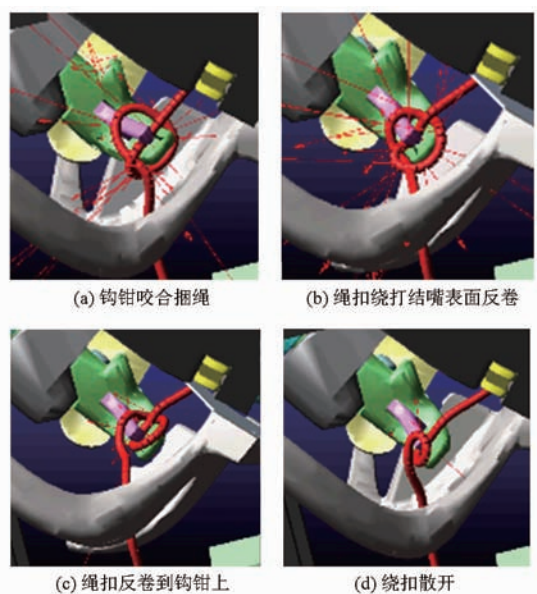


图 6 虚拟打结的割绳动作存在的问题

Fig.6 Problem of cutting rope motion of virtual knotting

于设计阶段检验打结器的结构改进和参数调整后的成结效果，保证打结器物理样机一次性制造的成功，大大降低了打结器制造的投入成本。

3.3 虚拟打结应用

打结嘴和夹绳盘动作时序差 φ 和打结嘴轴线与主轴轴线夹角 α 是打结器设计的两个基本参数^[1]。利用上述方法可对 φ 和 α 在不同组合下的打结器模型进行虚拟打结，以验证参数匹配是否合适。在此， α 取 98° ， φ 取 2.5° 、 7.5° 、 12.5° 、 17.5° 、 22.5° 共 5 组值。如图 8 所示，蜗杆轴锥齿轮与打结嘴锥齿轮安装相位差 ψ 取为 30° ，小齿盘上的不完全锥齿轮与大齿盘上的不完全锥齿轮的安装相位差按 $\varepsilon = \varphi + \psi$ 计算^[14]，当 φ 取 2.5° 、 7.5° 、 12.5° 、 17.5° 、 22.5° 时， ε 取 32.5° 、 37.5° 、 42.5° 、 47.5° 、 52.5° 。

修改打结器虚拟样机模型使小齿盘上的不完全锥齿轮与大齿盘上的不完全锥齿轮的安装相位差 ε 分别为 32.5° 、 37.5° 、 47.5° 、 52.5° ，利用前述方法对其虚拟打结，并与 φ 取 12.5° 时的虚拟打结过程对比，如图 9 ~ 13 所示。

由图 9 ~ 13 的图 a 可见，当 φ 为 2.5° 、 7.5° 、 12.5° 、 17.5° 、 22.5° 时，绕扣开始时夹绳盘相对打结嘴的转动逐渐超前，随着打结嘴与夹绳盘时序差 φ 增大，绕扣开始时捆绳沿夹绳盘逆时针方向捆绳夹持点向夹绳动片偏移，逐渐处于夹绳盘与夹绳动片形成的夹持闭合空间。当 $\varphi = 2.5^\circ$ 时，绕扣开始时夹绳盘未将捆绳送入夹绳动片夹紧，开始绕扣后捆绳被绳针带回，虚拟打结失败，表明小齿盘上的不完全锥齿轮与蜗杆轴锥齿轮啮合滞后大齿盘上的不完

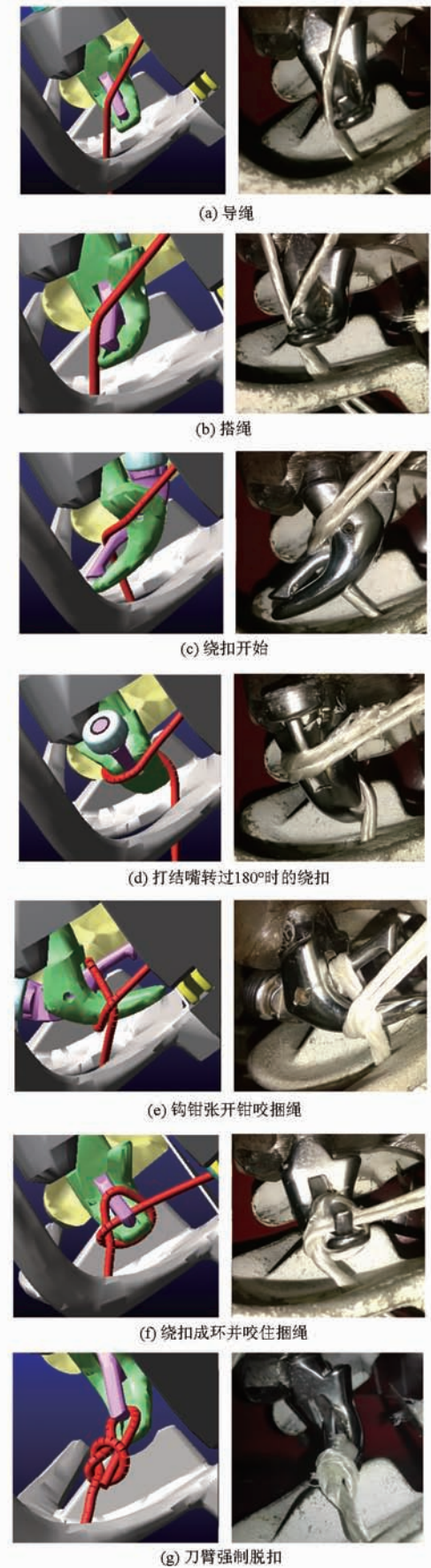


图7 虚拟样机与打结器样机打结过程对比
Fig.7 Contrast of knotting process between virtual prototype and knoter prototype

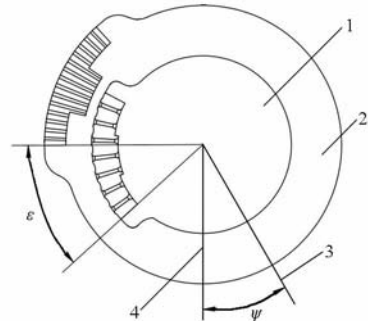


图8 齿盘锥齿轮安装相位差示意图
Fig.8 Installation phase difference between bevel gears on the gear-discs

1. 小齿盘 2. 大齿盘 3. 打结嘴轴心线 4. 夹绳盘蜗杆轴心线

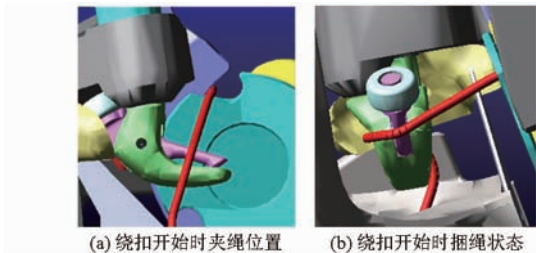


图9 φ取2.5°时的虚拟打结
Fig.9 Virtual knotting when φ is 2.5°

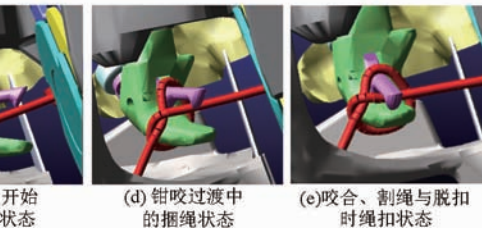
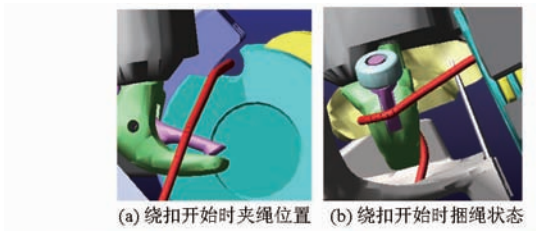


图10 φ取7.5°时的虚拟打结
Fig.10 Virtual knotting when φ is 7.5°

全锥齿轮与打结嘴轴锥齿轮啮合太多,即 φ 取 2.5° 过小。当 $\varphi = 7.5^\circ$ 时,绕扣开始时夹绳盘并未将捆绳完全送入夹绳动片,但在绳针夹持捆绳的辅助作用下,随着打结嘴旋转绕扣的同时捆绳被逐渐夹紧,不影响虚拟打结。当 $\varphi = 12.5^\circ$ 时,绕扣开始时捆绳恰好被夹绳盘完全送入夹绳动片夹紧。当 $\varphi = 17.5^\circ$ 和 $\varphi = 22.5^\circ$ 时,绕扣开始时捆绳已被夹绳盘与夹绳动片夹紧。

由图10c、10d可见,当 $\varphi = 7.5^\circ$ 时,捆绳处于钩钳末端与打结嘴末端连线的中间偏上位置,与勾钳距离较近,钩钳可咬住捆绳;由图12c~12e可见,当 $\varphi = 17.5^\circ$ 时,捆绳处于钩钳末端与打结嘴末端连线

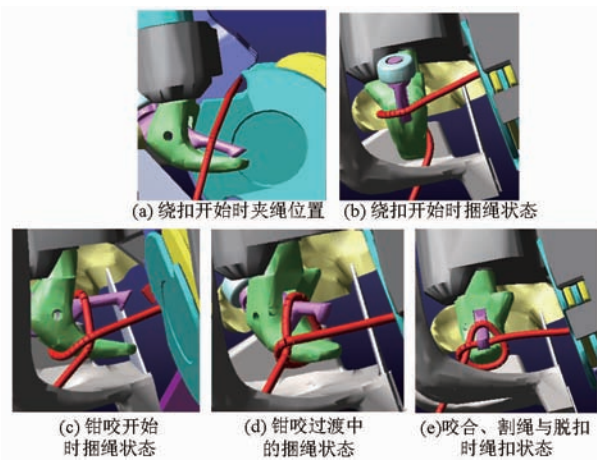


图 11 φ 取 12.5° 时的虚拟打结
Fig. 11 Virtual knotting when φ is 12.5°

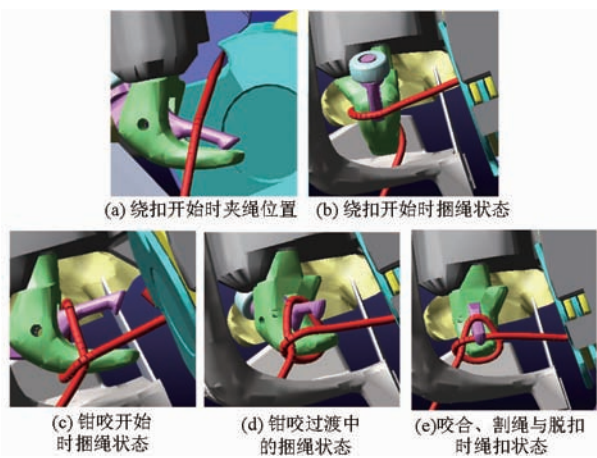


图 12 φ 取 17.5° 时的虚拟打结
Fig. 12 Virtual knotting when φ is 17.5°

的中间偏下位置,贴近打结嘴上表面,钩钳可咬住捆绳;由图 11c ~ 11e 可见,当 $\varphi = 12.5^\circ$ 时,捆绳处于钩钳末端与打结嘴末端连线的中间位置,钩钳可靠咬住捆绳,表明 $\varphi = 12.5^\circ$ 可获得钳咬捆绳最佳位置;而当 $\varphi = 22.5^\circ$ 时,捆绳在夹绳盘上的夹持点过低,钳咬时捆绳滑动到打结嘴侧方,导致钩钳无法钳咬住捆绳,钳咬动作失败而未能成结,如图 13c、13d 所示,表明 φ 取 22.5° 过大。

由上述分析,当 $\alpha = 98^\circ$ 、 φ 为 $7.5^\circ \sim 17.5^\circ$ 时,可以实现虚拟打结,表明小齿盘上的不完全锥齿轮

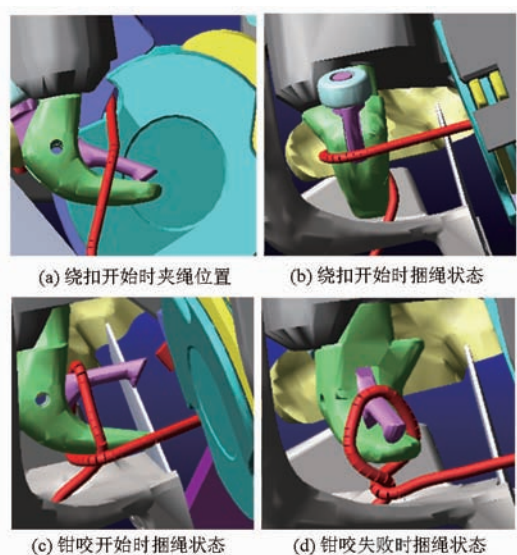


图 13 φ 取 22.5° 时的虚拟打结
Fig. 13 Virtual knotting when φ is 22.5°

与大齿盘上的不完全锥齿轮的安装相位差允许在 $(42.5 \pm 5)^\circ$ 间变动,约为半个齿的角度。

从图 9 ~ 13 可清楚看出打结嘴和夹绳盘动作时序差 φ 取不同值时,虚拟打结效果比解析计算后的数值模拟结果更加直观,对判定打结器参数匹配是否合适起到直观验证作用,有助于形成新的打结器设计方案。利用该方法能解决打结器设计后难以直观验证成结效果的问题,在设计阶段可发现设计缺陷,降低打结器制造的投入成本。

4 结论

(1)建立了完整的打结器刚柔接触虚拟打结实现方法,通过对打结器样机的成结动作与虚拟打结的仿真结果进行对比分析,验证了捆绳动力学模型与刚柔接触动力学仿真的正确性,可作为评价设计优劣、保证打结器一次性制造成功的有效方法。

(2)通过对双齿盘打结器打结过程的刚柔接触动力学仿真,验证了 ADAMS 的 Bushing 连接可解决大变形柔性绳索类模型的建立与仿真问题,对刚柔接触的机构设计与分析具有借鉴价值。

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