Mechanical model for double side self-propelled rolling machine based on rigid and flexible contact dynamics

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Abstract: The objective of the present research was to establish a mechanical model to study the performance of double side self-propelled rolling machine. There are two key models in the modeling process. The first model is the soft cover dynamics model, which is an important innovation in this study. And the insulation quilt was established based on the Macro-modeling technology. The second model is the double side self-propelled rolling machine virtual prototype model. By specifying multiple contact constraints and loadings between the soft cover dynamics model and the rigid component, the virtual prototype model was built successfully and the double side self-propelled rolling process was completely simulated. Moreover, the interaction mechanisms of the rigid and flexible coupling mechanics were investigated. The virtual rolling processes of different insulation quilt lengths were analyzed under different thickness treatments. The simulated results showed a good agreement with the experimental measurements, which suggested that the established model is an effective approach to evaluating and optimizing the rolling machine. The successful establishment of the mechanical model can facilitate the study of the performance of the product and further optimization, and also is of great significance to shorten the development cycle and reduce costs.

Keywords: contact dynamics, solar greenhouse, self-propelled rolling machine, mechanical model
DOI: 10.25165/j.ijabe.20221506.6485

Citation: Li Y M, Liu Y, Yue X, Li Z Q, Liu X A, Li T L. Mechanical model for double side self-propelled rolling machine based on rigid and flexible contact dynamics. Int J Agric & Biol Eng, 2022; 15(6): 38–43.

1 Introduction

Against the growing depletion of fossil fuel energy sources and environment degradation, solar greenhouse represents an efficient and sustainable agricultural method of production. The design objective of the solar greenhouse rolling machine is to drive the external insulation quilt to expand down and roll up, which plays an important role to strengthen the thermal insulation, increase the indoor temperature and improve production efficiency[1-8]. According to different power positions of the rolling machine, it can be classified as the rear rolling machine, the side rolling machine, the front rolling machine. Although these types of rolling machine have been developed in recent years, there still exist many problems in the design and use. For example, the rear rolling machine is hard to expand the insulation quilt, the front rolling machine does not automatically roll up the entire insulation quilt, and the side roll machine can only be used within the length of 60 m[7]. Deviation problem is a key problem commonly existing in the practical application of all kinds of rolling machine, which is affected by the weather condition, the improper installation, the inappropriate operation, and so on. The main reason for the rolling deviation is the unbalanced force on the roller shaft. What's worse, it even leads to the fracture of the roller shaft, thus affecting the greenhouse production and forming a safety hazard.

Some scholars have studied and designed the rolling machine to improve its working performance. Zhang et al.[9] improved the rear rolling machine by designing rope traction and releasing device. Yuan et al.[10] designed a joint device to solve the middle insulation quilt that cannot be rolled up automatically. Wang et al.[3] designed a double-power rolling machine with a horizontal correction device, which ensures the output torque balance at both ends of the roller shaft through its double-power mechanism in the working process. And intelligent control technologies such as position detection and horizontal correction device are adopted, which can effectively avoid the rolling deviation and roller shaft fracture[8]. Therefore, it is greatly significant to study the double side self-propelled rolling machine.

The insulation quilt is a large deformation flexible body. The conventional modeling method is dispersing the flexible body into a micro-fragments rigid body. For example, the rope objects can be discretized into many micro-cylinders[11], belt and track objects can be discretized into micro-pieces[12-16]. Due to the complex mechanical properties and the large flexible deformation of the insulation quilt, it is difficult to study the rigid and flexible contact dynamics during the rolling process, there has been no research on

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Received date: 2021-01-27 **Accepted date:** 2021-12-09

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simulating soft-covered and large-deformed objects. Moreover, the insulation quilt is limited by multiple contacts. It increases the difficulty of model establishment and the complexity of the numerical calculation, leading to low efficiency and even error in the solution. For this kind of problem, Shi et al.[18,19] used the segmented simulation method in virtual prototype simulation to maintain the calculation stability. Fang et al.[20] used the spatial operator algebra theory to describe multi-body systems, which eliminates the complexity of dynamic modeling and reduces the calculation amount. Pu et al.[15] replaced contact constraints with equal effectiveness approximation to reduce the calculation amount. Nevertheless, few scholars have carried out dynamic research on the rolling process of soft cover in solar greenhouse. It is urgent to create a soft cover dynamic model of the double side self-propelled rolling machine for the performance analysis under different movement mechanisms, control modes and complex environments.

To accurately reflect the flexibility and mechanical properties of the insulation quilt, this study proposed a novel method to establish the soft cover dynamics model by using the rotating pair to connect the micro-fragments lengthways and using the bushing force to connect the micro-fragments laterally. The insulation quilt was rolled up as a quasi-static process for force analysis, which provided a theoretical basis for numerical simulation. By using rigid and flexible contact dynamic modeling method, the model of double side self-propelled rolling machine was established based on the simplified greenhouse geometry and the soft cover dynamics model. On the basis of actual constraint and contact parameters, the dynamic process of virtual rolling under different insulation quilt thicknesses (i.e. 1.5 cm and 2 cm) and lengths (i.e. 200 cm and 300 cm) was calculated. What's more, a verification experiment of the rolling condition of the double side self-propelled rolling machine was carried out. And the experiment results could be served as the evaluation criterion to verify the correctness of the rigid-flexible contact dynamic simulation model.

2 Soft cover dynamics model

The insulation quilt of solar greenhouse is a large deformation flexible body. Such object can be discretized into a significant amount of micro-fragments for approximate modeling in the virtual prototype simulation[11]. Since the length of the micro-fragment is way smaller compared to the whole insulation quilt, the rigid body combination of the micro-fragments can be treated as the flexible body model. As a result, the deformation of insulation quilt thickness can be ignored. If the insulation was discretized into micro-fragment for modeling and was added constraints individually, it could be laborious and inaccurate. In order to address such problem, macro commands and conditional loop commands have been adopted to conduct batch modeling, impose constraints, apply contact and modify material properties of the insulation quilt.

The adjacent micro-fragments of each longitudinal insulation quilt were connected by a rotating pair, and those of each horizontal insulation quilt micro-fragment were connected by bushing force. The contact constraints added between micro-fragments are aimed to avoid the penetration that may induce failure during the simulation of rolling process. In addition, only those micro-fragments with contact conditions need to add contact constraints between them, which can improve the computational efficiency of the model solver[21].

By using the above methods, the mechanical properties of the insulation quilt are close to the real scenario, and the dynamic characteristics of the rolling machine therefore can be investigated thoroughly. The insulation quilt micro-fragments connected longitudinally and horizontally are shown in Figure 1.

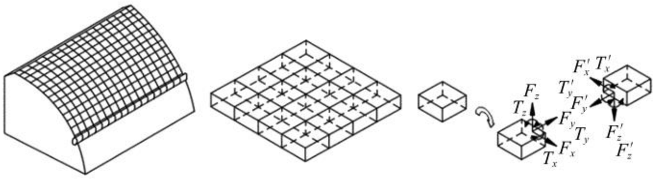


Figure 1 Schematic diagram of longitudinal and horizontal connections of insulation quilt

According to the mechanical theory, Bushing force[22] can be expressed as:

$$\begin{bmatrix} F_x \\ F_y \\ F_z \\ T_x \\ T_y \\ T_z \end{bmatrix} = K \begin{bmatrix} r_x \\ r_y \\ r_z \\ \theta_x \\ \theta_y \\ \theta_z \end{bmatrix} - C \begin{bmatrix} \upsilon_x \\ \upsilon_y \\ \upsilon_z \\ \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} + \begin{bmatrix} F_{x0} \\ F_{y0} \\ F_{z0} \\ T_{x0} \\ T_{y0} \\ T_{z0} \end{bmatrix} \tag{1}$$

where, K is the stiffness matrix of insulation quilt, which is a 6×6 diagonal matrix; C is the damping coefficient matrix of insulation quilt, which is also a 6×6 diagonal matrix; (F_{x0}, F_{y0}, F_{z0}) is the initial value of the component forces along the coordinate axis; (T_{x0}, F_{y0}, F_{z0}) is the initial value of moment along the coordinate axis; (r_x, r_y, r_z) is the relative displacement of the coordinate system at the center of the first micro-fragment relative to the second micro-fragment; (θ_x, θ_y, θ_z) is the relative rotation angle of the coordinate system at the micro-fragment center; (υ_x, υ_y, υ_z) is the relative velocity of the coordinate system at the micro-fragment center; (ω_x, ω_y, ω_z) is the relative angular velocity of the coordinate system at the micro-fragment center; (r_x, r_y, r_z), (θ_x, θ_y, θ_z), (υ_x, υ_y, υ_z), (ω_x, ω_y, ω_z) are automatically determined by the solver.

Diagonal elements of the stiffness matrix are calculated as follows:

$$\begin{cases} K_{11} = \dfrac{EA}{L} \\ K_{22} = K_{33} = \dfrac{JA}{L} \\ K_{44} = \dfrac{2JI}{L} \\ K_{55} = K_{66} = \dfrac{EI}{L} \\ J = \dfrac{E}{2(1+\mu)} \\ I = \dfrac{\pi}{64} D^4 \end{cases} \tag{2}$$

where, K_{11} is tensile stiffness; K_{22} and K_{33} are the shear stiffness; K_{44} is torsional stiffness; K_{55} and K_{66} are the bending stiffness; E is the elastic modulus of insulation quilt; J is shear modulus of insulation quilt; μ is Poisson's ratio; I is the moment of inertia of the insulation quilt center; A, D and L are the cross-sectional area, thickness and length of insulation quilt, respectively.

The flexible force between two adjacent micro-fragments depends on the dynamic properties, such as relative displacement, angle, linear velocity and angular velocity of the insulation quilt. The non-woven polypropylene fiber insulation quilt with a thickness of 0.02 m and a length of 3.5 m is employed for insulation quilt. According to the mechanical properties of polypropylene fiber, E=1.32 GPa, μ=0.35, J=0.49 GPa, I=1.92 mm^4,

K_{11} = 13502.5 N/m, K_{22} = K_{33} = 5012.3 N/m, K_{44} = 3920 N/m, K_{55} = K_{66} = 5012.3 N/m.

3 Rigid and flexible contact dynamics on the double side of self-propelled rolling machine

The double side self-propelled rolling process was realized by implementing the motors on both sides to drive the roller shaft. In this way, the driving force can be distributed more evenly with the motors on both sides. Therefore, each section of the roller shaft can be selected for mechanical analysis. The force analysis diagram of rolled insulation quilt is described as Figure 2.

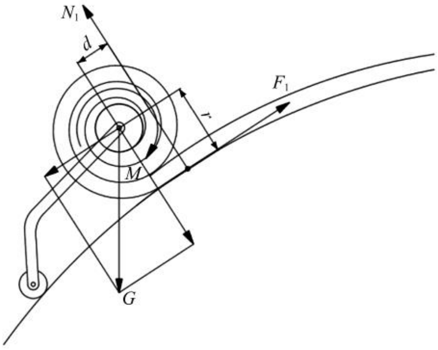


Figure 2 Force analysis diagram of rolled insulation quilt

The force on the insulation quilt includes the tension (F_1) of the insulation quilt on the rolled part, torque of the roller shaft (M) and gravity (G). And the gravity is decomposed into sliding force (F), pressure (N) and supporting reaction force (N_1). The supporting reaction force of the roof moves forward a certain distance (d) during the rolling process, therefore forming the rolling resistance. The distance increases with the increase of the radius of the insulation quilt, which is approximately proportional to r. According to the force analysis of the insulation quilt, the mechanical balance equation can be established as follows:

$$F_1 = F = G\sin\alpha \tag{3}$$

$$N_1 = N = G\cos\alpha \tag{4}$$

$$M = N_1 d + F_1 r = G \cdot d \cdot \cos\alpha + G \cdot r \cdot \sin\alpha \tag{5}$$

Set $k=d/r$, and combine Equations (3)-(5), it can be expressed as:

$$M = Gr(k\cos\alpha + \sin\alpha) \tag{6}$$

where, G is the total weight, kg. G represents the sum of the rolled insulation quilt weight (G_1) and the component weight (G_0). α is the gradient of greenhouse roof, °. G and r increase gradually with the rolling process, but α decreases gradually with the rolling process. And k is almost unchanged. The calculation is as follows:

$$G = G_0 + G_1 \tag{7}$$

$$G_1 = LS\rho g \tag{8}$$

where, G_1 is the weight of the rolled up part of the insulation, kg. L is the length of greenhouse, m; S is the length of the rolled part of the insulation quilt, m; ρ is the density per unit area of the insulation quilt, kg/m^2; g is the acceleration of gravity, m/s^2.

The insulation quilt is rolled into the spiral of Archimedes, whose polar coordinate equation is:

$$r = r_0 + \delta\Theta/2\pi \tag{9}$$

where, r is the radius of insulation quilt, m; r_0 is the radius of roller shaft, m; δ is the thickness of insulation quilt, m; Θ is spiral pole angle, rad. The relation between the insulation quilt radius (r) and the length of the rolled insulation quilt (S) is derived as follows:

$$S = \int_0^{\Theta} r\mathrm{d}\Theta = \int_0^{\Theta} (r_0 + \delta\Theta/2\pi)\mathrm{d}\Theta = r_0\Theta + \delta\Theta^2/4\pi \tag{10}$$

$$\Theta = 2\pi(\sqrt{(r_0^{\,2} + S\delta/\pi)} - r_0)/\delta \tag{11}$$

By substituting Equation (9) into Equation (10), the relationship between r and S can be written as follows:

$$r = \sqrt{(r_1^2 + S\delta/\pi)} \tag{12}$$

Equations (10)-(12) are substituted into Equation (6) to obtain the working resistance at different gradient:

$$M = (LS\rho g + G_0) \cdot (r_1^2 + S\delta/\pi)^{1/2} \cdot (k\cos\alpha + \sin\alpha) \tag{13}$$

where, L is the length of the greenhouse, m; S is the length of the rolled part of the insulation quilt, m; ρ is the density of insulation quilt, kg/m^2; G_0 is the mass of roller shaft, kg; r_1 is the radius of shaft, m; δ is the insulation quilt thickness, m; k is the proportional coefficient; α is the gradient, (°).

4 Simulation and verification of double side self-propelled rolling machine

4.1 Greenhouse parameters

The "LiaoShen-IV" solar greenhouse was taken as the research object. Due to complexity of the greenhouse roof, the continuous roof arcs can be simplified and scaled down, which is shown in Figure 3.

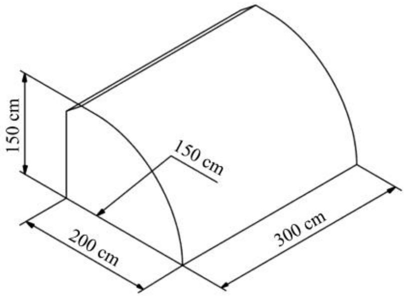
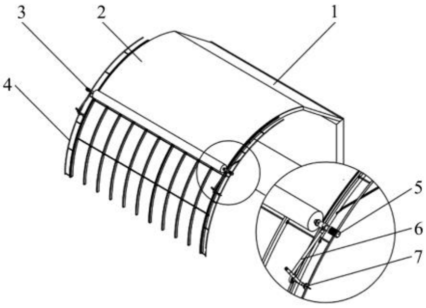


Figure 3 Simplified parameters for the solar greenhouse

The greenhouse roof is covered with the insulation quilt, with one end fixed on the top of the greenhouse and the other end connected to the roller shaft. In the double side self-propelled rolling machine, the two sides of the roller shaft are connected using two motors. The rolling and releasing processes are accomplished by changing the rotation direction of the motor. The motors are installed on the mounting frame of the track to ensure the working stability. Moreover, it can provide transverse limit for the insulation quilt. The two ends of the roller shaft can be synchronized by position detection and horizontal control, which helps avoid the problem of deviation in the rolling process. The structure of the double side self-propelled rolling machine is shown in Figure 4.



1. Greenhouse 2. Insulation quilt 3. Electric motor I 4. Track 5. Electric motor II 6. Motor mounting frame 7. Wheel

Figure 4 Schematic diagram of double side self-propelled rolling machine

4.2 Virtual prototype model of double side self-propelled rolling machine

To facilitate the batch modeling of insulation quilt micro-fragments, the virtual prototype model has been built based on the simplified greenhouse, and the parameters are set as follows: the length is 300 cm, the span is 200 cm and the height is 150 cm. Moreover, the components of double side self-propelled rolling machine are also simplified. Since the roller shaft length has little impact on the result, it is specified as the same as the greenhouse model. Moreover, the deformation and stress of the roller shaft during the rolling process are ignored. The virtual prototype model established by the macro modeling method[12-14] is shown in Figure 5.

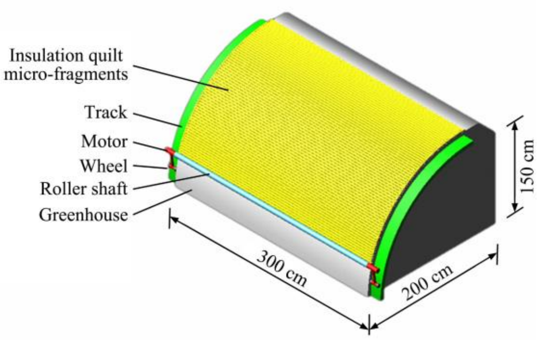


Figure 5 Double side self-propelled rolling machine virtual prototype model

4.3 Simulation details

For the virtual prototype model of a multi-contact constraint mechanical system, the solver uses a numerical iterative method to calculate the dynamic equation which is composed of complicated differential-algebraic equations. According to the contact judgment criteria adopted by the virtual prototyping technology, the solver combines the contact force into the generalized force matrix when solving dynamic equations[11]. The contact simulation between different components is achieved by defining the contact surface and contact type. In order to avoid penetration between the roller shaft and the insulation quilt micro-fragment, contact pairs are added between the roller shaft, with a total of 350 micro-fragments of insulation quilt and a total of 852 contacts. In addition, the rigidity and damping of the contact between every two longitudinal micro-fragments can be increased to an appropriate range to avoid penetration between them. It makes sure that the insulation quilt can be rolled up successfully.

The rotate speed of the roller shaft is about 2.8 r/min. So the roller drive is specified to 16.8°/s. According to the actual relationship between each part of the rolling machine, the corresponding constraints can be added. The detailed settings are listed in Table 1. Besides, the motor mounting frame is simplified in the model, which does not affect the correctness of the simulation. After applying the above drive and constraint parameters and loads (Table 1), the established model is then used for dynamic simulation.

In this study, the simulation model was verified using experimental measurement. Under the actual circumstance, the parameters of the insulation quilt have significant impact on the rolling performance. Therefore, two sets of simulations for changing the insulation quilt parameters were designed as follows: (1) Simulation under different insulation quilt thickness; (2) Simulation under different insulation quilt lengths. The simulation analysis conditions are shown in Table 2.

Table 1 Constraint settings in the model

Part 1 of the model that adds constraints	Part 2 of the model that adds constraints	Constraint type
The ground	Greenhouse	Fixed
The top of the insulation quilt micro-fragments	Greenhouse	Spherical pair
Insulation quilt micro-fragments	Adjacent insulation quilt in the same column	Revolving joint
The bottom of the insulation quilt micro-fragments	Roller shaft	Spherical pair
Insulation quilt micro-fragments	Non-adjacent insulation quilt micro-fragments in the same column	Contact pair
Insulation quilt micro-fragment	Adjacent insulation quilt micro-fragments of the same row	Bushing force
Insulation quilt micro-fragments	Greenhouse	Contact pair
Insulation quilt micro-fragments	Roller shaft	Contact pair
Shaft	Motor	Revolving joint
Motor	Wheel	Revolving joint
Wheel	Track	Contact pair

Table 2 Simulation analysis of working conditions

Simulation type	Main parameters of insulation material		Working conditions
	Thickness/cm	Length/cm	
Insulation quilt of different thickness	1.5	300	Double side motor drive
	2.0	300	Double side motor drive
Insulation quilt of different length	1.5	300	Double side motor drive
	1.5	200	Double side motor drive

4.4 Verification of virtual prototype

The overall structure of the greenhouse model includes a steel frame. The steel bars are bent, which are placed at a certain interval as in the greenhouse framework. The length, width and height of the simplified model are 300 cm, 200 cm and 150 cm, respectively. They are set the same as the simulation model, and the scale with the actual greenhouse size is 1:5. The verification model of double side self-propelled rolling machine is illustrated in Figure 6.

Figure 6 Verification model of double side self-propelled rolling machine

A 120 W AC deceleration motor was employed in this study. The motor is connected to the roller shaft through a coupling. As installed on the motor mounting frame, the wheels mounted on the motor mounting frame can move along the track. Before the verification test, the machine must be debugged, and the galvanometer is connected to the motor in series. At first, the no-load experiment was carried out. Moreover, the power system was adjusted to ensure the synchronous and stable operation of both sides of the rolling machine. At last, the physical testing was carried out, the measurement data change of the galvanometer was recorded and the data errors were analyzed. In the present research, the initial condition parameters of both the numerical simulation and the verification experiment are the same (Table 3).

Table 3 Setting of initial conditions for simulation and test

Greenhouse model length/cm	Greenhouse model width/cm	Greenhouse model height/cm	Motor speed /(°/s)	Mass of the roller shaft /kg	Diameter of the roller shaft/mm
300	200	150	16.8	16.08	66

During the experiment, the insulation quilt was rolled from the bottom to the specific position at the top. And multiple groups of the testing were conducted. The galvanometer was kept recorded. It is worth noting that each test was repeated more than 3 times.

The torque change of the motors is shown in Figure 7. In the case that the input voltage of the motor remains unchanged, the torque relationship formula $T = C_{\mathrm{T}} \cdot F_{\mathrm{m}} \cdot I \cdot \cos\phi$ shows approximately proportional[24]. In the initial stage of the rolling process, the positions of the two ends of the roller shaft were not synchronized due to the different motor speed. The greenhouse slope corresponding to the positions of the motors on both sides had a deviation of 3° at 30 s. By adjusting the motor rotation speed, the variation trend was close to synchronization with the positions on both sides at 50 s. Moreover, both ends of the roller shaft remained synchronized and stable until the end of the rolling process.

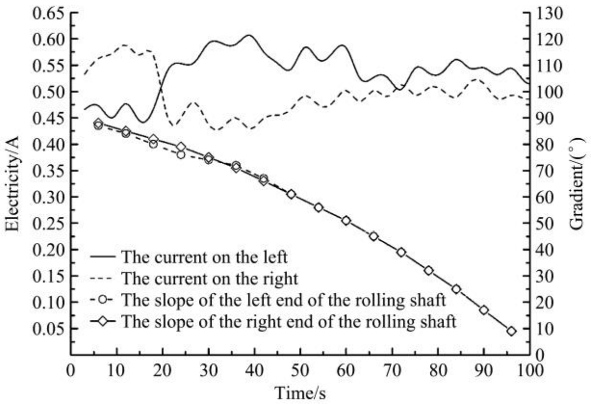


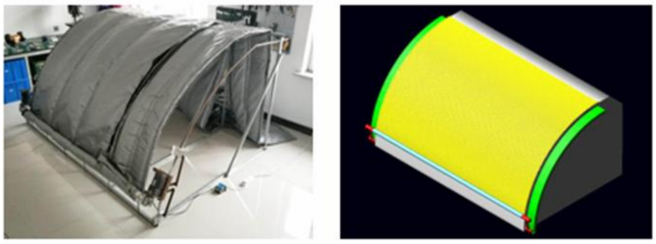
Figure 7 Variation of motors of double side self-propelled rolling machine

4.5 Virtual prototype simulation

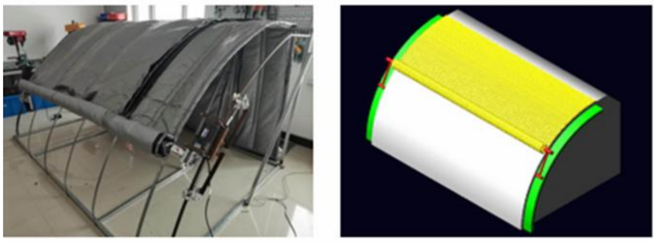
As shown in Figure 8, comparing the rolling process of the virtual prototype with the physical prototype of the double side self-propelled rolling machine, the multi-contact constraints in the virtual prototype model were appropriate. The modeling method of the insulation quilt was feasible, and the parameter settings were correct. Therefore, the large deformation and dynamic behavior of the insulation quilt can be simulated. Moreover, the contact constraint process between the insulation quilt and the rigid member under the double-sided driving can be completed.

The virtual prototype model can be used to observe the actual process of the roller shaft. Firstly, the roller shaft starts to rotate. Secondly, the roller shaft gradually rises while the insulation quilt is rolled up. Finally, the roller shaft stops at the roof slope of 10°. The results show that the virtual rolling method can be used to simulate and analyze the rolling machine.

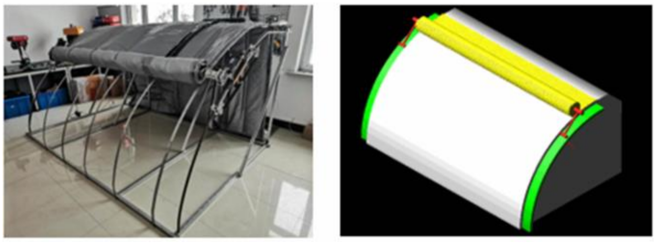
As shown in Figure 9, both the length and the thickness of the insulation quilt could affect the load of the roller shaft. The larger the length and thickness of the insulation quilt, the greater the maximum load of the rolling machine. The difference between the simulated results and the experimental measurements of the torque change remained within the range of 2 N·m. The distributions of the overall trends and running time were consistent. Moreover, the working position of rolling machine was on the top of the greenhouse under maximum load, emerging at 15 s with a



a. Begin to roll up

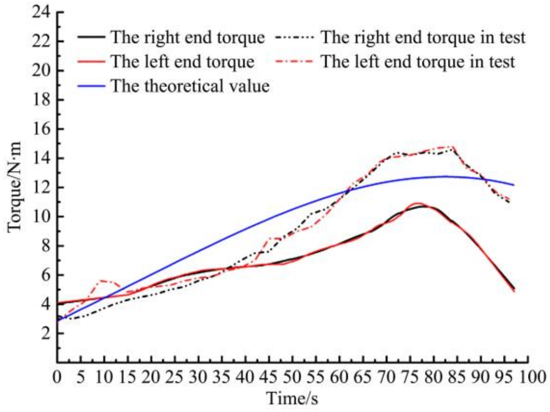


b. The insulation is rolled up and gradually raised

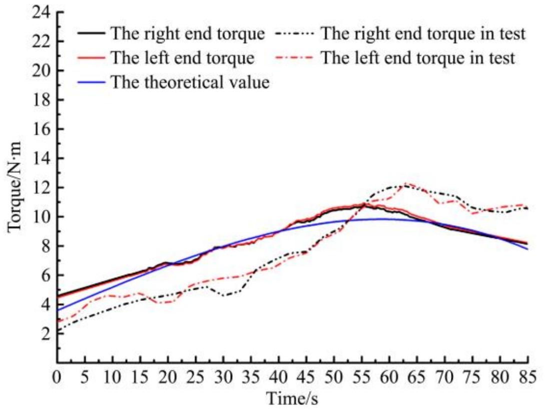


c. Roll to end at 10° slope of roof

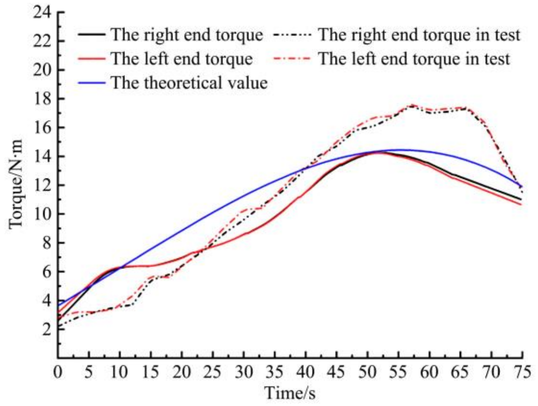
Figure 8 Comparison of rolling process and virtual prototype simulation



a. 1.5 cm thickness and 300 cm length



b. 1.5 cm thickness and 200 cm length



c. 2 cm thickness and 300 cm length

Figure 9 Working load curve of the double side self-propelled rolling machine under the condition of different thickness and length of insulation quilt

slope of 25° to 30°. The results agree with the theoretical value. Analyzing the cause of the error, the load error of the rolling process increased due to the simulation instability to a certain extent. What's more, the theoretical calculation of the rolling process was a quasi-static process, but the actual dynamic rolling process was slightly greater than the theoretical value.

5 Conclusions

A soft cover dynamic modeling method was realized in this study. It could solve the modeling problems of large deformation flexible insulation quilts. And a mechanical model for the double side self-propelled rolling machine was built to verify the application of bushing force and revolving joint. The simulation and experiment results of different work load were compared under the treatment of different insulation quilt thicknesses and lengths. The distributions of the overall trends and running time were in good agreement. Moreover, they were consistent with the theoretical value. The working position of rolling machine was on the top of the greenhouse under the maximum load, emerging at 15 seconds with a slope of 25° to 30°. The accuracies of the dynamics model were verified, which suggested an effective approach to study the contact dynamics behavior of rolling machine. The results could provide an important guidance for the development of rolling machine in solar greenhouse.

Acknowledgements

This work was financially supported by Liaoning Province Science and Technology Plan Project (2020-BS-134) and the Major Agricultural Project (2019JH110200003).

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