Motion Performance Analysis of New Tracked Vehicle Based on Plateau Characteristic Agriculture

Yiwei Shi[1, 2], Shichang Han[1, 2, *], Tang Xue[1, 2]

[1]Yunnan International Joint Laboratory of Intelligent Control and Application of Advanced Equipment, Kunming University of Science and Technology, Kunming 650500, China
[2]Kunming University of Science and Technology, Kunming, China
*Corresponding author's e-mail: han_shichang@163.com

Abstract. Aiming at the field of agricultural transportation with plateau characteristics, a bionic X-type tracked vehicle with an inerter is proposed. By comparing the theoretical calculation torque and simulation result torque of different road conditions and slopes, the feasibility and correctness of the tracked vehicle are verified. In the extreme case of climbing and crossing the ditch, the pitch angle is used as the evaluation standard to confirm that the tracked vehicle will not roll over under this road condition, which provides theoretical support for subsequent research.

Keywords: Tracked vehicle, Inerter, Crossing ability, Pitch

1 Introduction

According to the survey, the cultivated land below the 0-25 degree slope of the plateau characteristic agriculture in Yunnan Province accounts for 81.36 %, and the tracked vehicle has the advantages of low grounding specific pressure, good mobility, and strong obstacle crossing ability [1]. It has good trafficability and adaptability in the face of gravel, slopes, obstacles, and other roads, and is widely used in the field of agricultural transportation.

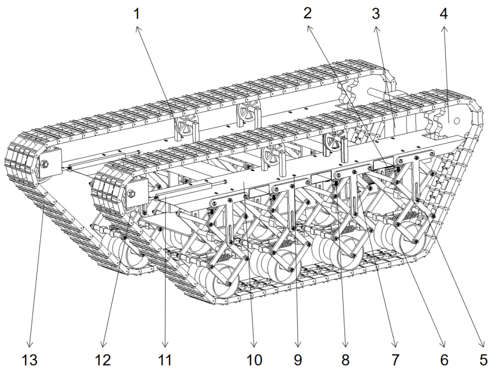
The emergence of the inerter [2] provides a new research direction for vehicle vibration reduction. Chen et al. [3] of Jiangsu University established a 1/4 model of the vehicle and optimized the suspension performance of the vehicle by improving the ISD (inerter-spring-damping) three-element structure. Yang et al. [4] studied a variety of vehicle suspension structures and found that the inertance coefficient provided by the inerter can effectively reduce the main frequency and offset the frequency of the suspension. Li et al. [5], based on the bionic vibration isolation theory, the research group designed a seat structure with an inerter and obtained the conclusion that the structure can effectively isolate low-frequency vibration isolation. The new bionic ISD structure applied to vehicle suspension is a new type of structure. Yang et al. [6] used displacement transmissibility and nod acceleration as evaluation criteria in the bionic suspension with inerter and verified that the bionic ISD structure of various pavements was superior to the SD structure, and the displacement transmissibility decreased with the increase of pavement complexity.

The new ISD structure is further applied to the plateau characteristic agriculture. In this paper, the pavement and ditch with plateau agricultural characteristics are taken as the research object, and a new bionic tracked vehicle with an inerter is studied to meet the trafficability and adaptability of the vehicle.

2 Structural Design of Tracked Vehicle

The design of the tracked vehicle is an important part of its driving stability, which is convenient for subsequent maintenance and design, and modularizes the chassis of the tracked vehicle. The tracked vehicle is divided into a suspension module, track module, and motor module. The overall structure of the tracked vehicle design is shown in Figure 1.

2.1 Overall Layout of the Tracked Vehicle



1-Branch chain wheel 2-Electrical machine 3-Gear box 4-Driving wheel 5-Bionic suspension 6-Loading wheel 7-T-steel 8-Inerter 9-Suspension mounting 10-Frame 11-Tensioning device 12-Tensioning wheel 13-Track

Fig. 1. Overall layout diagram of tracked vehicle.

2.2 Selection of Drive Module

The driving mode of the inverted ladder-tracked vehicle is generally divided into front drive, rear drive, and high drive [7]. The rear drive is adopted, and the contact end between the track and the ground is a tight edge, which will not produce large energy loss during operation. Electric drive is suitable for the driving mode of small tracked vehicles, which can instantaneously provide large torque to speed up. In summary, the vehicle uses a rear electric drive mode. The maximum torque generally appears when the maximum angle of the design climbing is designed. β is the climbing angle, r_x is the radius of the driving wheel, and the torque of the driving motor is calculated T_x :

$$T_x = \frac{r_x[ma + mg(f\cos\beta + \sin\beta)]}{i\eta} \tag{1}$$

The vehicle is designed as two drive motors, and the motor selection is calculated according to one half of the total weight of the vehicle [8], where i =9, f =0.2, $a = 0.3$ m/s^2 the calculation results in the preset maximum slope driving torque is 17.9 N·m. According to the calculated torque, the DC rare earth permanent magnet high-performance servo brushless motor is selected. The model is 180M-0250030C-E. The rated torque of the motor is 25 N·m, and the instantaneous torque of the motor is 55 N·m.

2.3 Track Module Design

Wheel-hole track [9] provides a reliable and effective way of power transmission, which is suitable for off-road conditions of complex terrain. When the vehicle is fully loaded, the bandwidth of the track and the length of the ground are set. According to the width of the track, it can be obtained by the empirical formula:

$$b = (0.9 \sim 1.1) \times 209 \times \sqrt[3]{m \times 10^{-3}} \tag{2}$$

The relationship ratio between the track grounding length d_1 of the tracked vehicle and the track gauge width B of the vehicle is as follows:

$$\varepsilon_b = d_1 / B \tag{3}$$

According to the vehicle structure, the appropriate driving wheel pitch circle radius r_x =115 mm and the radius of the tension wheel r_t =104 are selected. The design index is shown in Table 1.

Table 1. Tracked vehicle design standards.

Name of indicator	Parameter	Name of indicator	Parameter
Vehicle mass (kg)	250	Body size	1050×798×600
Load mass (kg)	100	Design speed	1.2
Climbing angle (°)	25	Energy	Electricity

3 Tracked Vehicle Design Standards

Based on the motion state of the tracked vehicle in the 0-25° slope, the climbing and climbing ditches are calculated and analyzed.

3.1 Longitudinal Stability Analysis

The reaction force of the ground to the vehicle is F_m, the vertical distance between the center of mass of the vehicle and the direction of the ramp is h_c, the distance between the center of mass of the vehicle and the direction of the ramp and the rear end and the front end is c_1 and c_2 respectively, and the longitudinal stability angle of the vehicle is β_1. The relationship is shown in Figure 2.

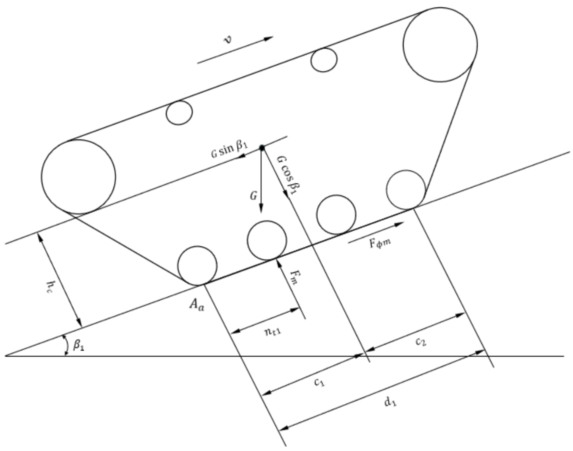


Fig. 2. Longitudinal stability analysis.

According to the analysis of the force of the tracked vehicle during the uniform climbing process. The moment of the reaction force of the tracked vehicle to the forward and backward bearing wheel connection point A_a is obtained:

$$F_m n_{t1} + G h_c \sin \beta_1 = G c_1 \cos \beta_1 \tag{4}$$

The simplified condition for the tracked vehicle not to overturn is:

$$\beta_1 \le \arctan \frac{c_1}{h_c} \tag{5}$$

Similarly, the rollover conditions of the vehicle during the downhill process are:

$$\beta_1 \le \arctan \frac{c_2}{h_c} \tag{6}$$

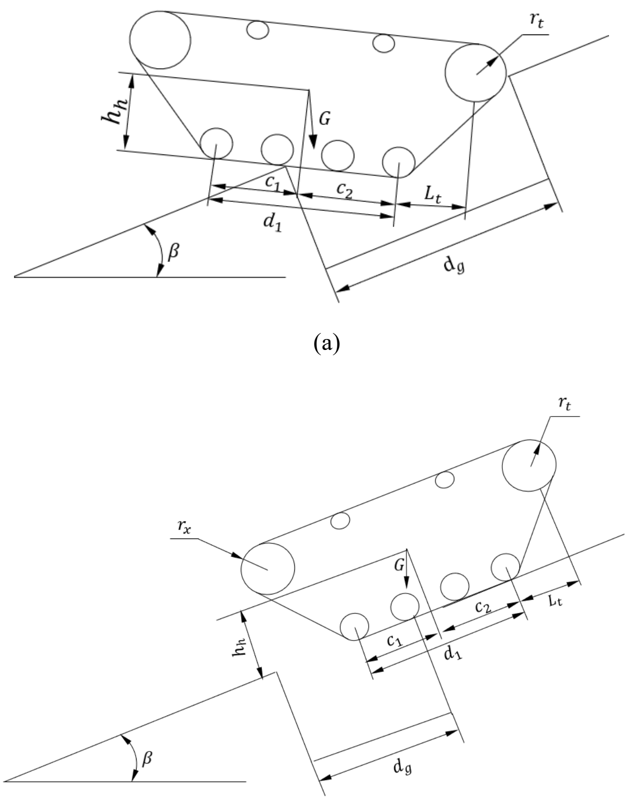
No-load and full-load h_c are 358 mm and 350 mm respectively, c_1 are 604 mm and 578 mm respectively, and $c_2 = d_1 - c_1$. Considering the no-load and full-load conditions, the maximum angle of longitudinal stability of the vehicle is 51.2°.

3.2 Analysis of Tracked Vehicle Climbing Across Ditches

The uphill crossing is divided into two stages. The first stage is when the center of mass falls into the ditch, and the tension wheel at the forward direction of the tracked vehicle contacts with the right wall, as shown in Figure 3 (a). In the second stage, the vehicle has a driving wheel in contact with the left wall. In this case, the vehicle has an elevation angle greater than 25°, and the rear end of the vehicle is in the ditch, and the center of gravity has been separated from the ditch, as shown in Figure 3 (b).

The maximum width of the slope gully is:

$$\begin{cases} d_g = \sqrt{(c_2 + h_h \tan\beta + L_{t1})^2 + {h_g}^2} + r_t \\ d_g = \sqrt{(c_1 - h_h \tan\beta)^2 + {r_w}^2} + r_w \end{cases} \tag{7}$$



(a)

(b)

Fig. 3. Uphill ditch schematic diagram.

The maximum width of the upper 25° slope is 466 mm.

3.3 Linear Dynamics Analysis of Tracked Vehicle

The pressure per unit area of the crawler is expressed by the Bekker formula:

$$p = z^n(\frac{k_c}{b} + k_\varphi) \tag{8}$$

p is the pressure per unit area of the track, z is the ground subsidence, k_c is the cohesive deformation modulus of the ground, k_φ is the friction deformation modulus of the ground. In practice, the tracked vehicle is not evenly distributed in the actual operation process, and its maximum pressure generally occurs at the position of the load-bearing wheel.

$$\begin{cases} \tan\alpha_h = t_p / D_c \\ \cos 2\alpha_h = 1 - 2\tan^2\alpha_h \end{cases} \tag{9}$$

α_h is the angle between the ground arc and the half of the track pitch. The sinkage is quite complicated in the actual situation. The front-end or back-end load-bearing wheel is consistent with the grounding arc angle of the crawler, and the force length of the grounding end is L_x, and then the sinkage of the front end of the crawler is z':

$$\begin{cases} L_x = 0.5D_c(\sin 2\alpha_h + \sin\alpha_h) \\ z' = \left[\dfrac{\dfrac{2F_{Ns}}{3bD_c}}{(\dfrac{k_c}{b} + k_\varphi)}\right]^{\frac{1}{n}} \end{cases} \tag{10}$$

When the tracked vehicle is running on the road, the work done by compacting the ground when passing through the land is E_p equal to the work done by the track consumption E_r, and then the driving resistance F_{Rc} is obtained:

$$F_{Rc} = \frac{1}{(n+1)\left(k_c + bk_\varphi\right)^{\frac{1}{n}}}\left(\frac{F_{Ns}}{L}\right)^{\frac{n+1}{n}} \tag{11}$$

Compaction resistance is usually simplified to rolling resistance F_{fm}:

$$F_{fm} = F_{Ns} f \tag{12}$$

When the tracked vehicle passes through the soft road, it will push the land under the ground all the time, and the bulldozing resistance is F_{Rb}:

$$F_{Rb} = b\left(czK_c + 0.5z^2\gamma K_r\right) \tag{13}$$

c is the cohesion coefficient, γ is the soil density, K_c and K_φ are calculated as follows:

$$\begin{cases} K_c = \left(N_c - \tan\varphi\right)\cos^2\varphi \\ K_\varphi = \left(\dfrac{2N_\gamma}{\tan\varphi} + 1\right)\cos^2\varphi \end{cases} \tag{14}$$

φ is the internal friction angle. N_c and N_γ are the bearing capacity coefficient of Taisha. The friction resistance F_i is opposite to the direction of the vehicle's movement, f_i is the internal friction coefficient, and 0.08 is taken. The dynamic equation of the average speed straight line is as follows:

$$\begin{cases} F_{fr} = F_P + F_{fm} \\ F_j = F_{fm} + F_P + F_i \end{cases} \tag{15}$$

The commonly used sandy loam and dry sandy soil were selected. The results are shown in Table 2:

Table 2. Linear dynamic calculation results of soft ground.

Parameter name	Clayey soil		Sandy loam		Dry sand	
	No-load	Full load	No-load	Full load	No-load	Full load
Sinkage (mm)	2.4	4.6	11.8	17.2	25.6	34.7
Torque (N·m)	28.2	35.4	31.3	43.8	37.1	51.7

The following will verify the calculation results of the above subsidence, climbing angle, and the angle of crossing the ditch on the slope.

4 Simulation Analysis and Verification of the Motion Performance of the Tracked Vehicle

Recurdyn is based on a fully recursive algorithm and is suitable for large-scale calculations. It has a dedicated crawler module. The scheme uses Recurdyn multi-body dynamics for verification.

4.1 Tracked Vehicle in Different Road Straight Line Simulation Check

In the simulation, the soft soil foundation is set up, and the linear motion simulation analysis is carried out in the horizontal direction. The desert is dry sand, and the plateau environment is mostly humus soil. The simulation results are shown in Figure 4.

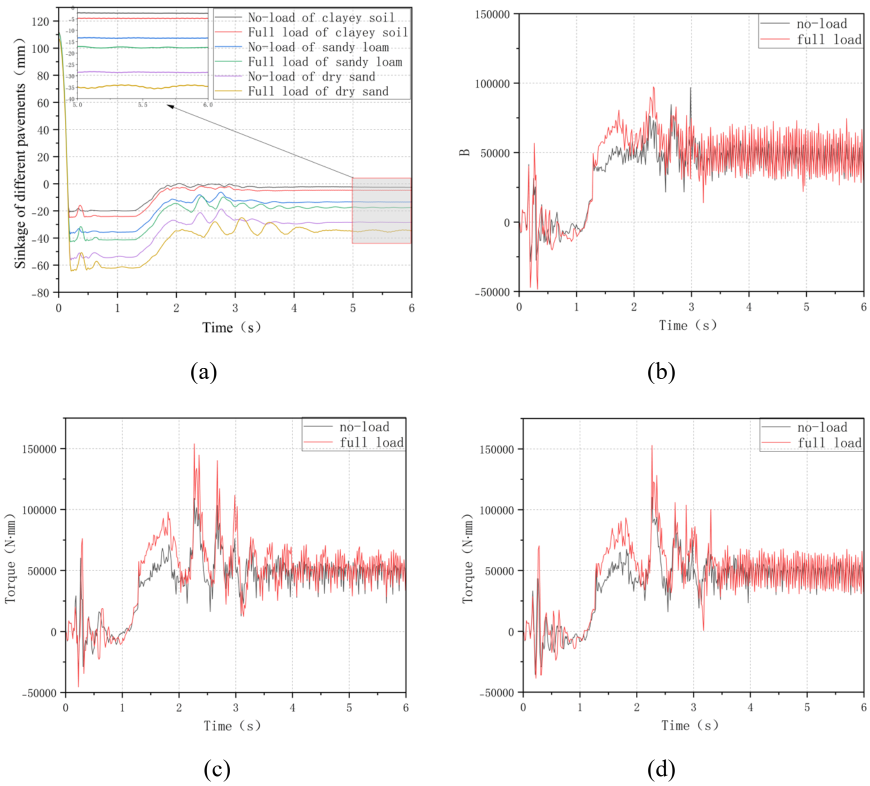


Fig. 4. Straight line soft ground simulation results.

According to the simulation results of Figure 4 (a), the subsidence of the vehicle on different roads under no-load and full-load conditions is shown in Table 3.

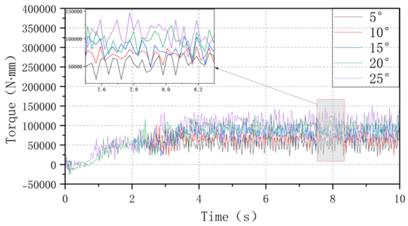
Table 3. Comparison table of subsidence of tracked vehicles.

Parameter name	Clayey soil		Sandy loam		Dry sand	
	No-load	Full load	No-load	Full load	No-load	Full load
Theoretical sinkage (mm)	2.4	4.6	11.8	17.2	25.6	34.7
Practical sinkage (mm)	2.6	4.9	13.5	18.1	28.4	36.0
Percentage error	8.3 %	6.5 %	14.4 %	5.2 %	10.9 %	3.7 %

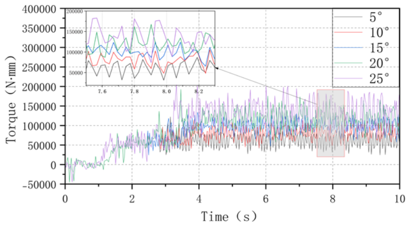
Through Figures 4 (b), (c), and (d), the subsidence is gradually deepened, because the bulldozing resistance and the grounding area increase the torque, and the vehicle begins to accelerate to the specified speed within 1 ~ 3 s. The vehicle torque increases and fluctuates when the speed reaches the maximum value. In dry sand, the no-load and full-load values were stable at 23.4-58.1 N · m and 29.0-70.4 N · m after 3.5 s, respectively. In the sandy loam environment, the no-load and full-load are stable at 30.1 ~ 60.0 N · m and 32.8 ~ 67.8 N · m. In operation, there is a gap between the track and the wheel, which makes the torque of the vehicle fluctuate, and the torque fluctuation decreases with the increase of the subsidence. In the clayey soil environment, the subsidence is small, and the percentage difference will be enlarged. There are differences in the weight of the other two ground environments. The weight is not linearly related to the subsidence, but the subsidence increment will gradually decrease with the increase of weight, so the difference of the vehicle is greater than that of the full load.

4.2 Tracked Vehicle Simulation on Slope Road

In the field of agricultural transportation, clear requirements are put forward for stability and obstacle-surmounting performance. In the software simulation, a slope with a slope of 25° is established, and the driving parameter is set to step (time, 1, 0, 3, 597.86D). The simulation results are shown in Figure 5:



(a) No-load



(b) Full load

Fig. 5. Slope torque of the tracked vehicle.

Figure 5 shows that the torque increases with the increase of the slope angle. Table 4 is the comparison table of theoretical calculation and simulation results:

Table 4. 5-25° Hard road torque verification calculation.

Angle	Parameter name	No-load	Full load
5°	Theoretical torque (N·m)	55.8	78.1
	Simulation torque range /mean value (N·m)	20.7-76.2/56.9	28.5-87.1/61.6
10°	Theoretical torque (N·m)	70.6	98.9
	Simulation torque range /mean value (N·m)	36.4-93.7/67.7	48.0-117.3/81.2

15°	Theoretical torque (N·m)	85.0	118.9
	Simulation torque range /mean value (N·m)	38.7-111.4/81.7	57.6-130.2/97.9
20°	Theoretical torque (N·m)	98.7	138.2
	Simulation torque range /mean value (N·m)	44.8-128.9/94.1	62.9-175.7/124.6
25°	Theoretical torque (N·m)	111.7	156.4
	Simulation torque range /mean value (N·m)	61.7-147.4/103.7	74.3-202.3/143.9

In summary, the torque difference between no-load and full-load increases with the increase of slope angle. The calculated value of the 5°-25° tracked vehicle on a slope is in good agreement with the simulation range and mean value, so the simulation results are general. The maximum torque is 202.3 N·m, which is in line with the motor selection standard. Table 5 shows the mean percentage error of torque.

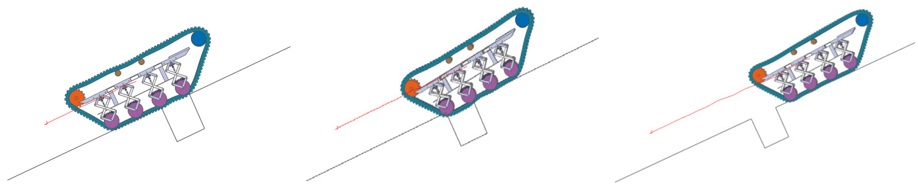
Table 5. Percentage error of climbing torque of the tracked vehicle.

Angle	Percentage error of torque	
	No-load	Full load
5°	2.0%	21.1%
10°	4.1%	17.8%
15°	4.0%	17.6%
20°	4.9%	9.8%
25°	7.7%	8.0%

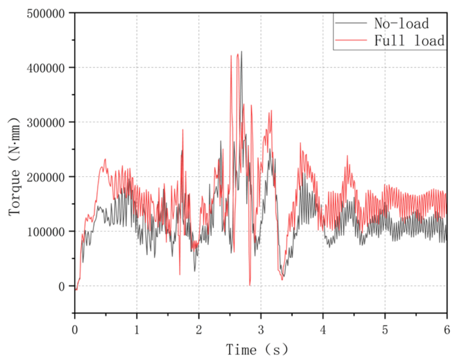
According to Table 5, the error of the tracked vehicle when it passes through the slope of 5°, 10°, and 15° is greater than that of other roads. Because the vehicle passes through the process from the horizontal to the slope, the broken surface of more than 20 degrees has a smooth buffer slope, so the impact is generated, which leads to a large percentage error in the upper slope. However, on the whole, the comparative analysis of the torque of the tracked vehicle structure is reliable, which verifies the unity of the simulation results and theoretical calculations of the vehicle on the slope.

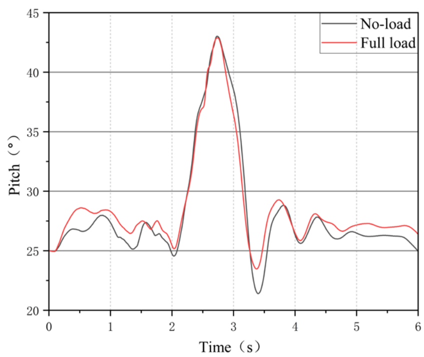
4.3 Simulation of a Tracked Vehicle Crossing a Ditch on a Slope

The previous theoretical calculation shows that the vehicle can pass through the ditch with a width of 466 mm on the 25° slope. To verify the trafficability of the vehicle on the slope, a slope with a ditch is established in the software, and the driving function of the driving wheel is step (time, 0.1, 0,1, 597.86D). Its crossing ditch and simulation results are shown in Figure 6.



(a)





(b) (c)

Fig. 6. Process and results of slope climbing and gully crossing.

As shown in Figures 6 (b) and (c), the vehicle initially stops on the slope, and the speed rises from 0.1-1s to 1.2 m/s. At this time, the torque increases rapidly, and the peak value of the fully-loaded vehicle reaches 228.9 N*m. In 1.6-3 s, the vehicle begins to cross the ditch, and the peak value reaches 412.5 N*m during the whole process of crossing the ditch and then decreases to gradually stable. When climbing over the ditch, the pitch angle of the vehicle is analyzed by the pitch angle, and the pitch angle of the vehicle is within the rollover angle.

In summary, the maximum torque appearing in the vehicle simulation is in line with the maximum value provided by the internal transmission ratio of the torque provided by the motor. The motor fully provides the torque involved in the vehicle's horizontal, slope, over-ditch, and slope over-ditch. The torque reached by the tracked vehicle on the non-hard road surface and during the climbing process is basically consistent with the previous calculation. The simulation verifies that the tracked vehicle is trafficable and feasible on the face of mountain and slope roads.

5 Conclusions

In this paper, a new type of bionic X-shaped tracked vehicle is designed. By comparing and analyzing the theoretical calculation and simulation results, it is concluded that the tracked vehicle will sink when it moves on the soft ground. The tracked vehicle meets the design requirements of the plateau characteristic agricultural vehicle under the motion state of the straight line, climbing and climbing over the ditch. The torque of the theoretical calculation is consistent with the simulation results, and the correctness of the theoretical modeling is checked.

In the most complex climbing and ditching stage of the tracked vehicle, the pitch angle is used as the evaluation standard, and the maximum rollover angle is the upper limit, which verifies that the vehicle's design has good trafficability and stability.

References

1. Wang Weiwei, Chen Liqing, Yang Yang, et al. Research status and prospect of chassis technology of agricultural machinery. J. Agricultural Machinery Journal, 2021, 52(08): 1-15.
2. SMITH M C, WANG F C. Performance benefits in passive vehicle suspensions employing inerters. J. Vehicle System Dynamics, 2004, 42(4): 235-257.
3. Chen Long, Yang Xiaofeng, Wang Ruochen, et al. Research on the performance of improved ISD three-element vehicle passive suspension. J. Automotive Engineering, 2014, 36 (03): 340-345.
4. Yang Xiaofeng, Du Yi, Liu Yanling, et al. Study on the influence of inertia coefficient on the frequency characteristics of vehicle ISD suspension system. J. Vibration and Shock, 2018, 37 (07): 240-246.
5. Li Xi, Han Shichang, Yang Suo. Research on vibration isolation performance of bionic seat with inerter. J/OL. Mechanical Science and Technology, 1-10 [2024-10-10].
6. Yang Suo, Han Shichang, Li Xi. Design and vibration reduction performance analysis of bionic X-shaped suspension with inerter. J. Journal of Ordnance and Equipment Engineering, 2024, 45 (06): 260-266.
7. Lu Hao. Stability study of inverted trapezoidal tracked vehicle based on Recurdyn. D. Central North University, 2023.
8. Wang Zhitong. Research on key technologies of coal mine rescue tracked vehicle. D. Taiyuan University of Technology, 2018.
9. Li Feng. Design and research on the chassis of rubber crawler bucket wheel reclaimer for salt. D. Tianjin University of Science and Technology, 2016.