STRUCTURAL DESIGN AND POWER SIMULATION OF TRACKED ELECTRIC TRACTOR BASED ON ECONOMY

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基于经济性的履带式电动拖拉机结构设计与动力仿真

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DOI: https://doi.org/10.35633/inmateh-74-75

***Keywords:** Facility agriculture; Electric tractor; Finite element; Optimisation; Simulation*

ABSTRACT

In view of the serious pollution of traditional fuel machinery in facility agriculture production, in order to facilitate the operation of tractors in greenhouses, in this study, a small tracked electric tractor suitable for facility agriculture was designed and analysed. In the early stage of design, the basic frame of pure electric tractor was established, the final chassis layout is determined through force analysis and layout setting; after the three-dimensional modeling of the tractor structure, the finite element analysis using the software Ansys verified that the stiffness and strength of the frame met the design requirements; the dual-motor drive structure was optimized. The maximum deformation of the track chassis frame was 0.685 mm, the maximum equivalent elastic strain of the track chassis frame was 0.0131 mm, and the maximum stress of the track chassis frame was 25.818 MPa, which was less than the yield stress of the selected material of the frame. ADVISOR was used to simulate the electric tractor during rotary ploughing and unladen transport operations. The simulation results showed that the dual-motor drive mode saved more than 20% of energy consumption compared with the single-motor mode and the transmission efficiency was improved by about 17%, which improved the operational efficiency of the tractor, and provided theoretical and data support for the subsequent prototype production.

摘要

针对设施农业生产中传统燃油机具污染较为严重的问题，为了便于在温室大棚内开展拖拉机作业活动，本研究设计并分析了一种适用于设施农业的小型履带式电动拖拉机。在设计前期，确立了纯电动拖拉机的基本框架，通过受力分析和布局设置，确定了最终底盘布局；在对拖拉机结构进行三维建模后，使用软件 Ansys 进行有限元分析验证了车架刚度与强度满足设计要求；其中履带底盘车架的最大变形为 0.685mm，履带底盘车架的等效弹性应变最大值为 0.0131mm，履带底盘车架的最大应力是 25.818MPa，小于车架选用材料的屈服应力。同时对双电机驱动结构进行优化，采用 ADVISOR 进行电动拖拉机在旋耕和空载运输作业时的模拟仿真，仿真结果表明，双电机驱动模式相比单电机模式能够节约能耗 20%以上，且传动效率提升了 17%左右，提高了拖拉机的作业效率，为后续样机试制提供了理论与数据支持。

INTRODUCTION

Facility greenhouse environment is relatively closed, crops on the environmental quality requirements are particularly high, in addition to the ground level, suitable moisture, good light conditions, as far as possible to reduce air pollution *(Liu et al., 2022).* For this reason, there is an urgent need for research on electric tractors with low energy consumption, low pollution, low noise, high efficiency and other advantages.

Crawler electric tractor has the following characteristics: low centre of gravity, higher coefficient of adhesion, better adhesion conditions under the same power, able to play a better traction performance with better trafficability *(Matveev et al., 2013)*; differential steering mode more suitable for the structure of the dual-drive motor, with a smaller turning radius, able to operate in the narrow space of the facilities of agricultural operations; grounding ratio is low, able to reduce compaction of the soil structure, less likely to form a subsoil

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layer. Low ground specific pressure reduces compaction of the soil structure, making it less likely to form a plough subsoil when working in facility agriculture *(Oelen et al., 1994).*

Electric tractor refers to the tractor driven by electricity, including the energy system, drive system, the whole machine system, of which the energy system for electric tractor work to provide electric power, mainly composed of battery packs, can be used as auxiliary energy to improve the discharge performance through the range extender, fuel cell or supercapacitor, the direction of the electric power flow is controlled by the DC/AC converter. The drive system consists of drive motor, transmission system and travelling device, providing mechanical power for the whole machine to travel and traction. The complete machine system is an electric tractor whole that contains other parts such as the body and suspension device on the basis of the energy system and the drive system, and is used to realise the electric tractor driving, lifting agricultural implements as well as steering and braking according to the requirements *(Song., 2023)*.

Drawing on the existing power transmission system structure of pure electric vehicles, the power transmission system of the whole machine in this paper is designed, and the preliminary design of the whole machine layout framework is shown in Fig. 1. Then, the electric drive system of the whole machine is designed, and the main components of the whole machine are identified.

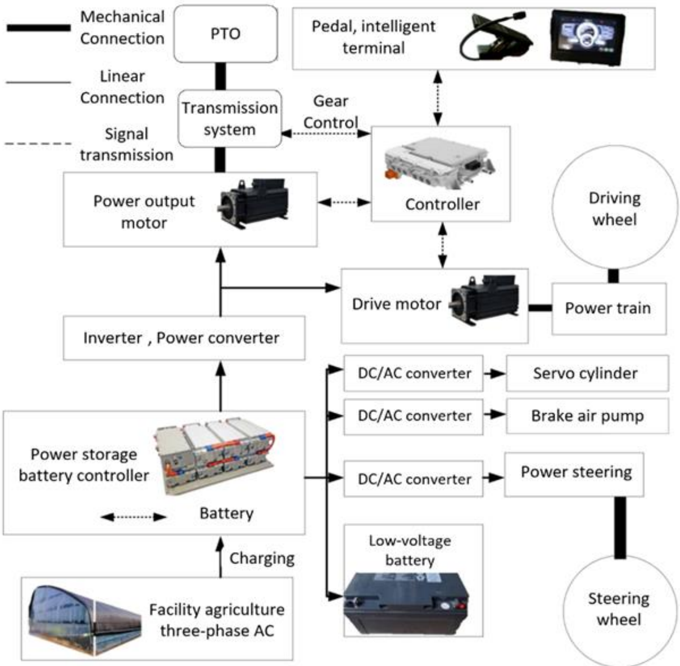

Fig. 1 - Basic frame of pure electric tractor

MATERIALS AND METHODS

Force Analysis

The force analysis of tracked electric tractor is shown in Fig. 2. The tractor is in contact with the ground through the track plate, the coefficient of friction is relatively high, the contact length is L_0, the combined force of all the support reaction forces of the ground on the track plate is F_Z, the distance between the centre of the combined force and the central axis of the drive wheel is x_y, the reaction forces in the vertical and horizontal directions when hanging and pulling the implement are F_y, F_D, the torque is M_z, and the point of force is at the centre of the track at the point O_1.

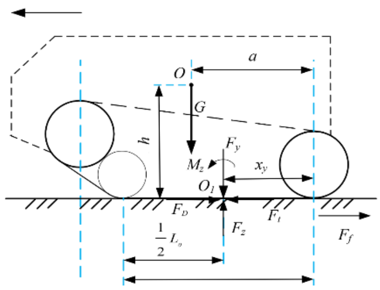

Fig. 2 - Force analysis of crawler electric tractor

The traction balance equation for a tracked motorised tractor in the horizontal direction is:

$$F_t = F_f + F_D \tag{1}$$

Balance of forces in the vertical direction equation:

$$F_Z = G + F_y \tag{2}$$

The position of the centre of pressure can be obtained from the moment balance equation:

$$x_y = \frac{Ga + F_y(x_c + 0.5L_0) - M_z}{F_z} \tag{3}$$

When the centre of pressure of the track is located at the centre of the track, the soil will be subjected to the most uniform force, low compaction and small damage to the soil structure, so the centre of pressure should be located at the centre of the track as far as possible in the design of crawler type electric tractor *(Song et al., 2023)*.

Facility agriculture-oriented electric tractor does not have a closed cab, a windshield, it has a simple shape and small windward surface, while being driven at a low speed, so the impact of air resistance on electric tractors is ignored. Based on the above analysis, the walking balance equation is established as follows:

$$F_t = F_f + F_i + F_j + F_D = mgf\cos\alpha_G + mg\sin\alpha_G + \delta m\frac{du}{dt} + F_D \tag{4}$$

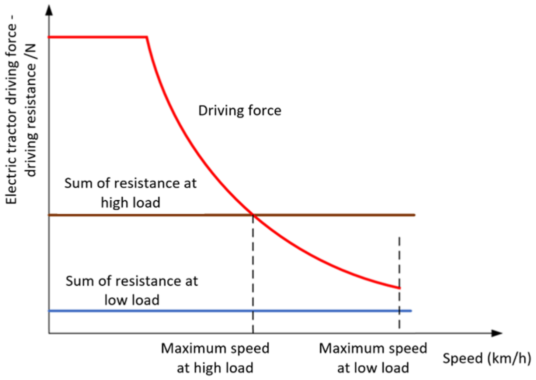

Fig. 3 - Driving force-resistance balance diagram

According to the above analysis to draw the driving force curve of the electric tractor shown in Figure 3, when the rolling resistance and traction force of the electric tractor is larger, the tractive force curve of the electric tractor and the intersection of the resistance curve corresponding to the speed of the electric tractor traction of the implement for the maximum speed, at this time *(Song, 2023)*, the driving motor works in the constant power stage, the driving force is equal to the sum of the other resistances; when the tractor is unloaded or the ground conditions are better, the driving force is always greater than the sum of the resistance. The driving force of the tractor is always larger than the sum of resistances, at this time the maximum speed of the electric tractor is limited by the maximum speed of the drive motor, which can be obtained from:

$$u_{\max} = \frac{0.377rn_{\max}}{i} \tag{5}$$

In the facility agriculture field, the land is flat and the slope angle is small, so only the acceleration performance of agricultural electric tractor on flat ground is studied, which can be obtained according to the travelling balance equation of electric tractor operation:

$$a_j = \frac{F_t - F_D - F_f}{\delta m} \tag{6}$$

Structural Design

Through reasonable settings, the balanced distribution of traction force can be improved to overcome the problem of unbalanced force caused by the gravity balance of the rotary ploughing mechanism itself, and to avoid the situation of deviation and tilting of the travelling route in the course of the tractor, as shown in the structure of the electric crawler rotary ploughing machine in Fig. 4.

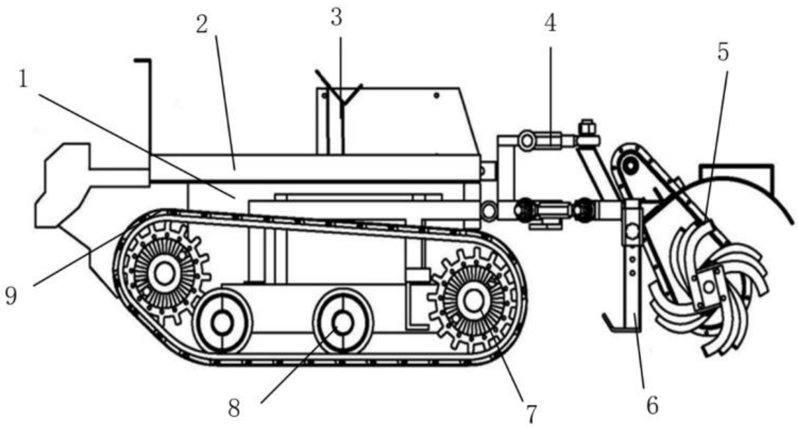

Fig. 4 - Crawler electric tractor structure diagram

1. Battery pack; 2. Rack; 3. Control system; 4. Suspension rack; 5. Rotary cultivator; 6. Support frame; 7. Drive wheel; 8. Support wheel; 9. Tracks

Frame Condition and Load Analysis

When the electric crawler tractor is working, the load situation of the frame is more complicated *(Zhao et al., 2022)*. This section focuses on analysing the changes of the frame architecture in the static state, and carrying out a static structural analysis of the force state of the frame when the crawler tractor is fully loaded. It is assumed that the electric crawler tractor carries out uniform linear motion on the ground with good road conditions *(Gong et al., 2021)*. At this time, the main sources of force on the frame are the gravity of each device and the frame, as well as the gravity of the mounted small rotary plough acting on the frame. The applied loads on the frame are shown in Table 1.

Table 1

Specific loads for crawler tractors

Name	Electromotor	Bodywork and transmission	Battery pack	Control system	Small rotary plough
Load size (kg)	100 kg*2	80 kg	45 kg	30 kg	120 kg

Considering the up and down bumps of the vehicle frame when driving a and operating on uneven road surface, the maximum dynamic load factor under full load bending condition should not be greater than 2.5. Since the electric tractor is mainly used in the gently sloping terrain of the facility agricultural plantation, in this paper, the dynamic load factor of the crawler chassis for driving and operating under bending condition is taken to be 2.

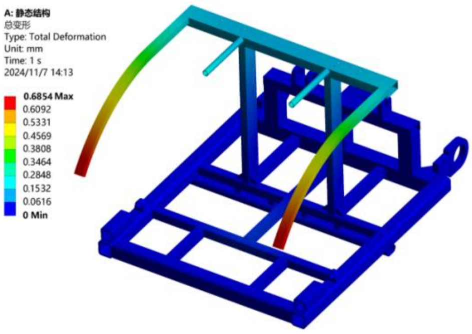

Fig. 5 -Total deformation

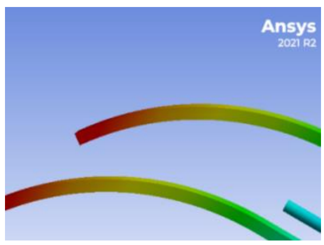

Fig. 6 - Maximum total deformation

As can be seen from Fig. 5 and Fig. 6, the maximum deformation of the tracked chassis frame is 0.685 mm, which is relatively small compared to the overall structure of the tracked chassis frame, so it can be assumed that the rigidity of the tracked chassis frame can satisfy the hydrostatic design requirements.

The maximum deformation occurs in the bumper at the upper end of the frame, because the engine is fixed to the two longitudinal beams at the front side, which is equivalent to the pressure exerted on a cantilever beam, and due to the deformation of the longitudinal beams at the front, the bumper is subjected to the tension force of the upper side wall, so it is reasonable that the maximum deformation occurs.

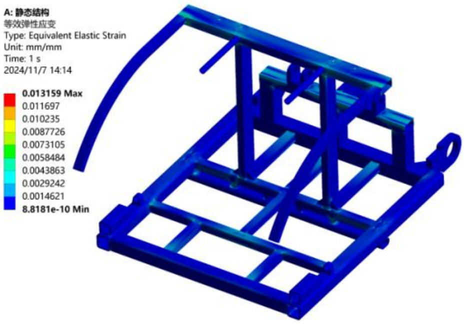

Fig. 7 - Equivalent elastic deformation

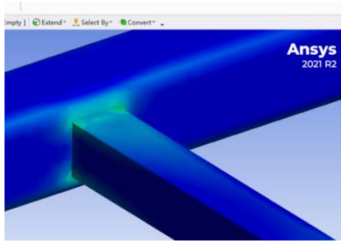

Fig. 8 - Maximum equivalent elastic deformation

Figure 7 and Figure 8 show that the maximum equivalent elastic strain of the tracked chassis frame is 0.0131 mm, which occurs below the connection between the front longitudinal beam and the front cross member, and is less than the maximum allowable deformation of the tracked chassis frame material. This indicates that the rigidity of the designed tracked chassis frame complies with the design conditions.

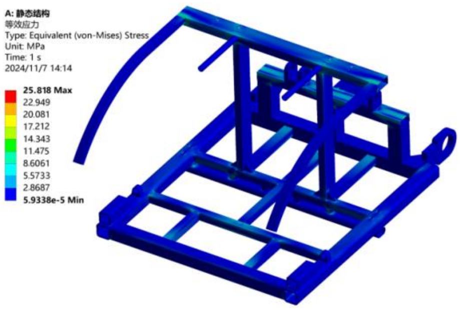

Fig. 9 - Equivalent stress

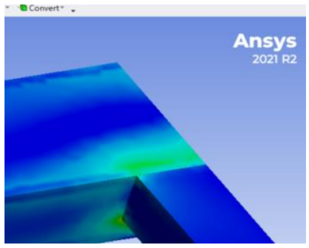

Fig. 10 - Maximum equivalent stress

According to Fig. 9 and Fig. 10, the maximum stress of the tracked chassis frame is 25.818 MPa, which is less than the yield stress of the materials selected for the frame, which indicates that the strength of the materials used for the tracked chassis frame is in accordance with the structural design requirements. The maximum stress occurs under the connection between the frame and the rear cross member, because the engine is mounted on the rear longitudinal beam, which is squeezed by the front longitudinal beam. In order to achieve the required stress reduction, it is possible to consider increasing the wall thickness in these areas or welding a rib plate. From the above analysis, the frame stiffness and strength of tracked electric tractor can meet the static design requirements under full load bending condition.

Whole Machine Power Simulation

Power Consumption and Power Utilisation of Crawler Tractors:

When calculating the rated traction, the tractor being in the ploughing and transport when the driving speed is slow, the tractor in the working state of the force analysis can be ignored when the air resistance, according to the horizontal direction of the force balance of the tension balance equation *(Bing, 2021)*:

$$F_q = F_t + F_f \tag{7}$$

where: F_q - driving force, N; F_t - traction resistance, N; F_f - rolling resistance, N.

The traction resistance formula can be expressed as:

$$F_t = z b_1 h_k k \tag{8}$$

where: z - number of ploughshares; k - soil specific resistance, N/cm^2; h_k - depth of ploughing, cm; b_1 - width of individual ploughshares, cm.

As the tractor is mostly used for ploughing, its rated tractive effort is determined by the average tractive effort during ploughing. Since the tractor works in a complex environment and carries a wide range of ploughing implements, the resistance to work fluctuates accordingly, so it is necessary to retain a reserve of 10-20% of the traction capacity *(Gao et al., 2008)*. The rated traction force of an electric tractor can be expressed as follows:

$$F_{TN} = (1.1 \sim 1.2) F_T \tag{9}$$

Electric tractor in the work of the total energy consumed is equal to the energy output of the battery, so by the formula (7) on both sides multiplied by the tractor in the operation of the traveling speed, both the power arithmetic formula:

$$P = F_T \frac{V_j}{3.6} + F_f \frac{V_j}{3.6} w \tag{10}$$

where V_j - travelling speed during operation, km/h.

Determine the Chassis Layout

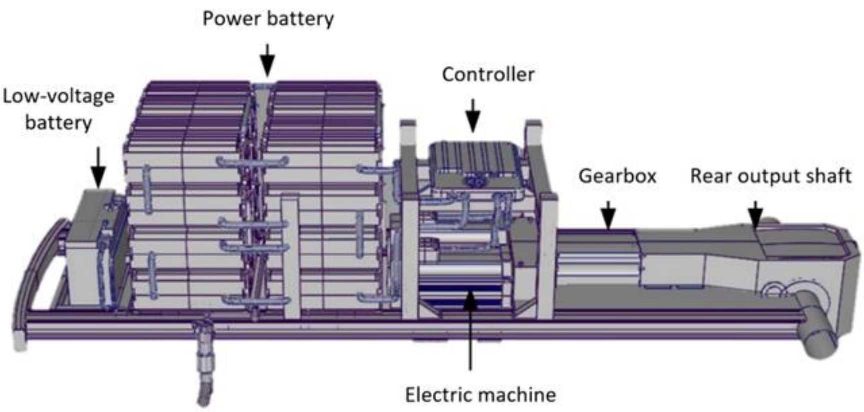

Fig. 11 - Chassis layout of the prototype

The electric tractor drive structure scheme designed in this paper is shown in Figure 11, two motors for steering drive at the same time, the two motors were installed to the left drive shaft and the right drive shaft, saving the space of the vehicle, the front drive motor is only responsible for the traction operation of the front wheels, the rear drive motor is responsible for the rear wheels of the traction operation and ploughing and other mechanical output. In this paper, the permanent magnet synchronous motor is chosen as the drive motor, with rated power of 5 KW and rated speed of 1500 min. The permanent magnet synchronous motor has the advantages of large starting torque, high efficiency, strong overload capacity, small volume, light weight, etc., and it can meet the requirements of the motor for the electric tractor in the special environment. The motor can meet the requirements of electric tractor in special environment.

Establish Simulation Test Conditions

ADVISOR was used to simulate the electric tractor during ploughing and transport operations, and the whole vehicle model, battery model, transmission controller model, and drive motor model were established. The whole vehicle model is based on the force analysis diagram under tractor traction operation. From the driving equilibrium equations, driving torque equilibrium equations and the load influence on the driving wheels, the whole vehicle simulation model is established in Simulink and then embedded into the ADVISOR simulation model. The battery model is composed of the battery charge equations and the loads on the drive wheels *(Zhang et al., 2017)*. The battery model is modelled in ADVISOR by the relationship between the state of charge (SOC) of the battery and the current, voltage and temperature, and the fuzzy inference algorithm is used to build the transmission simulation control model in Simulink and then embedded into ADVISOR. The drive motor model is built based on the relationship between the measured motor efficiency and the speed and torque. Due to the low travelling speed when the tractor is working, the air resistance is neglected in the model *(Wang et al., 2023)*.

The electric tractor can be roughly divided into two types of operation: unloaded transport and rotary ploughing, and this paper mainly establishes the simulation of these two working conditions, and the working conditions of transport operation are shown in Fig.12, with reference to the EUDC test conditions. The running time is 400 s in total, the running distance is 1.06 km, the maximal speed is 12.7 km/h, and the average speed is 9.42 km/h. Figure 12 shows the simulated working conditions of the rotary tillage operation of the electric tractor. Due to the complexity of the rotary tillage operation environment of the electric tractor, the traction force on the tractor will have a small range of changes, and the operating speed will remain unchanged while fluctuating up and down with the rated traction force as the benchmark to simulate the different conditions occurring in the operation of the tractor *(Liu et al., 2023)*.

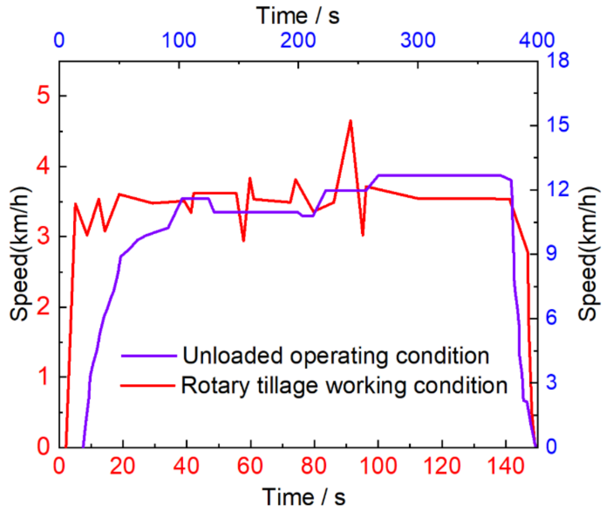

Fig. 12 - Unloaded operating condition and Rotary tillage working condition

RESULTS

Rotary Tillage Operations

The rotary ploughing conditions are determined by adjusting the controller to increase the resisting torque on the drive wheels so that the resisting torque is equal to the resisting torque of the tractor during ploughing, and by adjusting the accelerator pedal control to change the speed during operation, resulting in the drive wheel output torque, power consumption and transmission efficiency during ploughing. Figure 13 shows the output torque of the drive wheels, and the peaks appearing in the figure are the extra loads encountered by the tractor when ploughing. The two-motor drive uses a two-motor average torque distribution strategy to achieve the optimum drive effect.

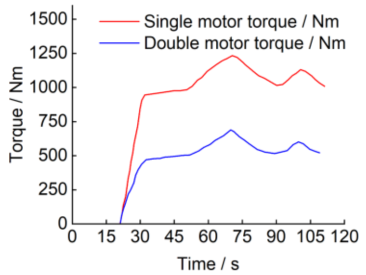

Fig.13 -Rotary tillage output torque

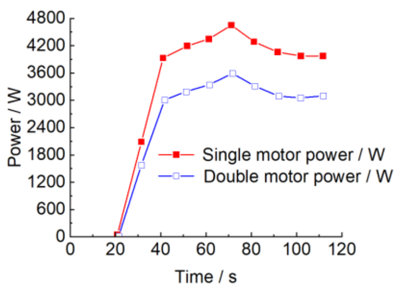

Fig. 14 - Output power

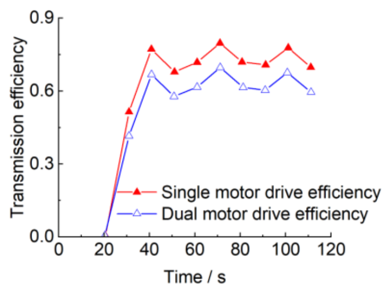

Fig. 15 - Transmission efficiency

Fig. 14 shows the power consumed by the two drive modes, the power consumed increases as the load increases, when the tractor and ploughs travel at a steady speed, the power consumed by the single motor drive mode is greater than that of the two-motor drive mode. The energy consumed by the tractor during operation is equal to the total energy output from the battery, and the power of the tractor is determined by multiplying the traction force by the travelling speed which gives the power consumed. From Fig.14, it can be seen that the average power consumed by the dual motors is 2876.95 W, and the average power in the single motor operation is 3725.3 W. Therefore, the dual motors save 22.7% of the energy consumption compared to the single motor operation.

Figure 15 shows the transmission efficiency of the two drive structures. Due to the two-motor drive structure designed in this paper, saving part of the transmission mechanism, reducing the energy loss caused by wear and tear of components, as can be seen from the transmission efficiency change curve in the figure, the transmission efficiency of the single-motor transport reaches an average of 0.61, the transmission efficiency of the double-motor operation averages 0.69. So, the transmission efficiency of the two-motor drive structure is 11.5% higher than that of the single-motor-driven structure.

Unloaded Operating Condition

The brake controller is adjusted so that the output torque at the drive wheels is equal to the load torque of 297 Nm for rated transport, yielding the power consumption, torque and transmission efficiency for normal driving *(Chen et al., 2023)*.

As can be seen from Fig.16, when the tractor reaches the uniform speed driving state after acceleration, the vehicle output torque is relatively stable, with only minor fluctuations, and the dual-motor drive mode has a smaller torque than the single-motor drive mode.

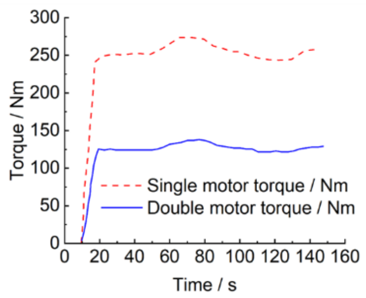

Fig. 16 - Unloaded motor torque

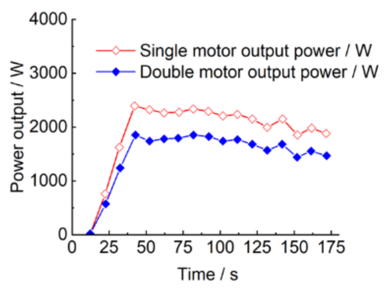

Fig. 17 - Output power

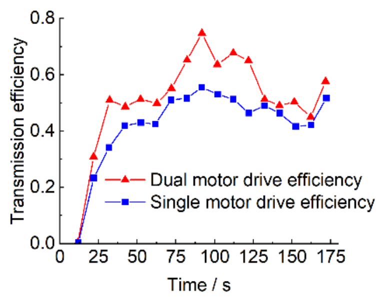

Fig. 18 - Transmission efficiency

From Fig.17, it can be seen that the power consumed by the tractor is relatively stable when driving at a constant speed, which is much smaller than that consumed during rotary ploughing operation, and the average power consumed during single-motor transport is 2012.3 W, while the average power consumed during dual-motor operation is 1609.2 W. The dual-motor drive mode saves 20.3% energy consumption compared with single-motor operation.

From the transmission efficiency shown in Fig. 18, it can be seen that the higher the tractor travelling speed, the greater the transmission efficiency, specific data are shown in the table2.

Table 2

Motor Efficiency Data

Time/s	Dual motor	Average efficiency	Single motor	Average efficiency
11.75	0.01		0.00	
21.84	0.31		0.23	
32.20	0.51		0.34	
42.29	0.49		0.42	
52.13	0.51		0.43	
62.73	0.50		0.42	
72.10	0.55		0.51	
82.22	0.65		0.52	
91.82	0.75	0.52	0.55	0.43
101.71	0.64		0.53	
112.03	0.68		0.51	
121.87	0.65		0.46	
132.24	0.51		0.49	
141.84	0.49		0.46	
151.44	0.50		0.42	
162.05	0.45		0.42	
171.65	0.58		0.52	

Combining the graphs gives an average transmission efficiency of 0.43 for the single motor mode and 0.52 for the dual motor mode, with the dual electric drive mode having an average of 17% higher transmission efficiency than the single motor mode.

CONCLUSIONS

The power system of dual-motor electric tractor mainly includes the electric drive assembly with the drive motor as the core and the power output assembly with the power output. Compared with the single-motor centralised configuration, the rotational speed of the power output shaft is easier, and the application of the dual-motor also improves the tractor's dynamics, which is combined with the simulation analysis to determine the final chassis layout.

The crawler electric tractor was subjected to force analysis, layout setting, etc., and the frame structure was statically analysed by combining with Ansys software, and the stiffness and strength of the frame of the crawler electric tractor met the requirements of the static design under the working condition of full-load bending.

A simulation model of a small electric tractor for facility agriculture was constructed and the parameters of each component in the simulation model were set. The power consumed by the single-motor two-wheel drive mode is 1.29 times that of the two-motor drive mode in ploughing operation, and the power consumed by the single-motor drive is 1.25 times that of the two-motor drive mode in transport operation. The two-motor drive mode simplifies the transmission system, and the transmission efficiency is 52% in transport operation and 69% in ploughing operation, while the transmission efficiency of the single-motor drive mode is 43% in transport operation and 61% in ploughing operation. The simulation results verify the accuracy of the designed electric tractor parameter matching, and lay a foundation for the subsequent prototype trial production.

ACKNOWLEDGEMENT

The project supported by the Shandong Province agricultural machinery equipment research and development innovation plan project (No. 2018YF005).

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