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Control Strategy of Torque Distribution for Hybrid Four-Wheel Drive Tractor

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Abstract: Based on the analysis of the operating conditions of the tractor, a Hybrid four-wheel drive tractor is proposed, and formulate the torque distribution control strategy based on fuzzy control, to control the driving wheel slip rate of the Hybrid four-wheel drive tractor in the high traction efficiency operating range of the tractor. The vehicle model of the Hybrid four-wheel drive tractor is established in AVL-CRUISE software, and the torque distribution control strategy based on fuzzy control is established in MATLAB/Simulink software. The AVL-CRUISE and MATLAB/Simulink co-simulation was carried out based on the plowing condition of the tractor. The simulation results show that the torque distribution control strategy based on fuzzy control can control the driving wheel slip rate of the Hybrid four-wheel drive tractor in the high traction efficiency operating range, the power performance of the Hybrid four-wheel drive tractor is improved, while the engine runs smoothly and is always in the high-efficiency range of engine operation, and the economy is better.

Keywords: parallel hybrid; hybrid tractor; slip rate; torque distribution; fuzzy control; four-wheel drive

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1. Introduction

The tractor is the most widely used agricultural machinery. Its main job is to mount agricultural implements for operation in the field and for transportation on the road [1,2]. With the change in tractive force, the slip rate of the tractor also constantly varies [3,4]. With the increase in tractive force, the slip rate will also increase. Excessive slip rate on the one hand will affect the tractor's tractive force, wasting engine power; on the other hand, excessive wheel slip will damage the soil structure and cause increased tires wear, reducing efficiency [5,6]. Related research shows that the wheel tractor will have high traction efficiency if the slip rate is controlled between 10% and 15% [7], so the slip rate of the tractor drive wheel needs to be controlled to improve the tractor's traction efficiency. The current research on changing the slip rate of tractor drive wheels is mainly focused on changing the tillage depth [8,9]. The change in tillage depth will have some effect on the growth of crops [10,11]. The torque distribution of the tractor drive wheels directly affects the slip rate of the drive wheels [12–14], and the four-wheel drive tractor can effectively reduce the slip rate of the drive wheels [15]. The traditional four-wheel drive tractor uses a splitter to distribute the torque of the front- and rear-drive wheels, and the arrangement of the mechanical components is not convenient, at the same time, the four-wheel drive tractor with the splitter is not able to distribute the front- and rear-drive wheel torque flexibly, and the working condition is poorly adapted. The electric drive system can conveniently arrange the power source, realize the front- and rear-independent drive, and flexibly distribute the torque of the front- and rear-drive wheels [16–18]. Some researchers in the vehicle field have proposed a compound hybrid electric vehicle configuration, which adds a front-drive motor to drive the front wheels based on the power-split hybrid electric vehicle configuration, and Toyota's Highlander vehicle uses three motors and an engine to improve the fuel economy and power of the vehicle [19]. However, both compound hybrid electric vehicle configurations and power-split hybrid electric vehicle configurations have complex control systems and high costs. Cong Guo et al. proposed coordinated control of torque distribution and drive anti-skid for front- and rear-independent drive electric vehicles in the vehicle field, which achieved good results and improved the dynamics of four-wheel drive Electric vehicles [20]. However, the current Electric vehicle has the problem of short range, which is not conducive to agricultural production. Liyou Xu et al. proposed an Extended range four-wheel drive electric tractor [21], which distributes the torque of the front- and rear-drive wheels of the tractor and achieved good results. However, the Extended range electric vehicle configuration has the problem of too many energy conversions and low energy utilization.

The four-wheel drive tractor with a splitter has the problem of difficult component arrangement and not being able to flexibly distribute the torque of the front- and rear-drive wheels; the compound hybrid configuration has the problem of complex structure and difficult design of the control system; the pure electric system has the problem of short-range time; and the Extended range electric vehicle configuration has the problem of low energy utilization with a high number of energy conversions. In this paper, by analyzing the defects of the existing tractor power system, a Hybrid four-wheel drive tractor is proposed by adding the front-drive motor to the parallel hybrid tractor, the parameters of the main components are calculated and matched, and a torque distribution control strategy is developed to distribute the torque to the front-drive motor, the rear-drive motor and the engine. The effectiveness of the torque distribution control strategy was verified by joint simulation of AVL-CRUISE and Matlab/Simulink. A theoretical basis is provided for the design and development of the Hybrid four-wheel drive tractor.

2. Hybrid Four-Wheel Drive Tractor Working Condition Analysis

The main work of the tractor is in the field mounted agricultural equipment for plowing, harrowing, fertilization, seeding, and other operations, as well as road transport operations. Plowing condition is the highest frequency of tractor working condition, but also the most basic and heavy working condition, the tractor plowing condition analysis, can fully reflect the performance of the tractor, and this paper to plowing condition as an example of the tractor analysis.

The longitudinal mechanics of the tractor during operation is modeled as

$$F_{qt} = F_f + F_i + F_w + F_j + F_g = F_{qr} + F_{qf}, \tag{1}$$

where, F_{qt}, total tractor tractive force; F_f, rolling resistance; F_i, gradient resistance; F_w, air resistance; F_j, acceleration resistance; F_g, plowing resistance; F_{qr}, rear-drive wheel tractive force; F_{qf}, front-drive wheel tractive force.

Air resistance and acceleration resistance are negligible during tractor operation. The resistance of tractor operation mainly comes from plowing resistance, rolling resistance, and gradient resistance.

$$F_{qt} = F_f + F_i + F_g = F_{qr} + F_{qf}, \tag{2}$$

$$F_i = Gi \tag{3}$$

$$F_f = Gf \tag{4}$$

where, G, tractor gravity; i, road gradient; f, rolling resistance coefficient.

Tractor operation will produce slip, reducing the efficiency of the tractor. Research shows that as the tractive force increases, the slip rate will also increase.

The relationship between tractive force and adhesion coefficient can be expressed as:

$$F_q = \varphi F_z, \tag{5}$$

$$\varphi = \varphi_{\max}\left(1 - e^{-\frac{\delta}{\delta^*}}\right) \tag{6}$$

where, φ, drive wheel tractive force coefficient; $\varphi_{\max}$, maximum adhesion coefficient; δ, slip rate; δ^*, characteristic slip rate; F_q, drive wheel tractive force; F_z, drive wheel vertical load.

Therefore, by reasonably distributing the tractor front- and rear-drive wheel, tractive forces can effectively reduce the slip rate and improve the traction efficiency of the tractor.

The tire model describes the ground forces on the tires as a mathematical function [22]. The selection of the tire model, which directly affects the prediction of the traction performance of the drive wheels, is crucial for the drive system modeling. In this paper, the tire model uses the Duggof tire model [23], and the tractive force expression of the drive wheels is:

$$F_q = \begin{cases} F_z\left[\varphi - \varphi^2 \frac{F_z(1-\delta)}{4c\delta}\right], & \frac{c\delta}{1-\delta} \geq \frac{\varphi F_z}{2} \\ \frac{c\delta}{1-\delta} & , \frac{c\delta}{1-\delta} < \frac{\varphi F_z}{2} \end{cases}, \tag{7}$$

where, c, tire longitudinal stiffness.

The tractor distributes the front- and rear-drive wheel tractive forces according to the tractive force distribution coefficient (k) to obtain:

$$F_{qf} = F_{qt}k, \tag{8}$$

$$F_{qr} = F_{qt}(1-k) \tag{9}$$

From Formulas (7) and (8), the front-drive wheel tractive force is

$$F_{qf} = \begin{cases} \left(F_{zf}\left[\varphi_f - \varphi_f^2 \frac{F_{zf}(1-\delta)}{4c\delta}\right] + F_{qr}\right)k, & \frac{c\delta}{1-\delta} \geq \frac{\varphi F_{zf}}{2} \\ \left(\frac{c\delta}{1-\delta} + F_{qr}\right)k & , \frac{c\delta}{1-\delta} < \frac{\varphi F_{zf}}{2} \end{cases}, \tag{10}$$

where, k, tractive force distribution coefficient; F_{zf}, front-drive wheel vertical load; φ_f, front-drive wheel tractive force coefficient.

From Formulas (7) and (9), the rear-drive wheel tractive force is

$$F_{qr} = \begin{cases} \left(F_{zr}\left[\varphi_r - \varphi_r^2 \frac{F_{zr}(1-\delta)}{4c\delta}\right] + F_{qf}\right)(1-k), & \frac{c\delta}{1-\delta} \geq \frac{\varphi F_{zr}}{2} \\ \left(\frac{c\delta}{1-\delta} + F_{qf}\right)(1-k) & , \frac{c\delta}{1-\delta} < \frac{\varphi F_{zr}}{2} \end{cases}, \tag{11}$$

where, F_{zr}, the rear-drive wheel vertical load; φ_r, the rear-drive wheel tractive force coefficient.

From Formulas (10) and (11), it can be obtained that there is a high degree of nonlinearity between the front-drive wheel tractive force, the rear-drive wheel tractive force, and the tractive force distribution coefficient of the tractor.

3. Hybrid Four-Wheel Drive Tractor Model Analysis

3.1. Hybrid Four-Wheel Drive Tractor Drive System Model Analysis

The drive configuration of the tractor has an important impact on the dynamics of the tractor. The traditional four-wheel drive tractor uses a mechanical splitter to distribute the torque of the front- and rear-drive wheels, which has a complex structure and difficult arrangement of mechanical components, and cannot adjust the tractive force distribution of the front- and rear-drive wheels according to the road conditions, and has a low traction efficiency [24]. The power system of the Hybrid four-wheel drive tractor in this paper includes the front-drive system and the rear-drive system. The front-drive system includes the front-drive motor, which is responsible for driving the front-drive wheels. The rear-drive system includes the engine and the rear-drive motor, the engine is the main power source and the rear-drive motor is the auxiliary power source, the power of the engine and the rear-drive motor output power to the rear-drive wheels through the coupling action of the power coupler. The engine and the rear-drive motor can work separately or jointly to provide power to the rear-drive wheels. No mechanical connection between the front-drive system and the rear-drive system, convenient for the arrangement of components, and the front- and rear-drive wheel tractive force can be flexibly adjusted according to the road conditions, to develop a flexible front- and rear wheel torque distribution control strategy, in order to make the tractor slip rate control in a more reasonable range, to improve the tractor traction efficiency, the Hybrid four-wheel drive tractor power system used in this paper is shown in Figure 1.

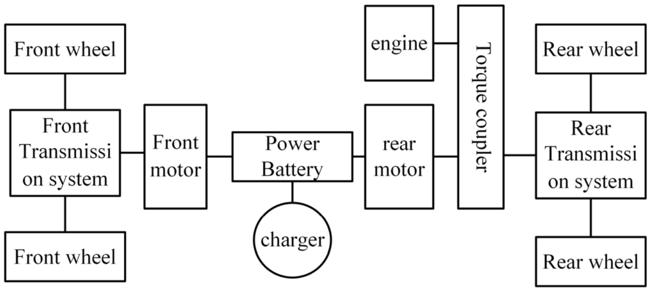

Figure 1. Hybrid four-wheel drive tractor power system.

3.2. Power System Matching Design

3.2.1. Determination of Rated Tractive Force

Rated tractive force is the tractor in the horizontal lot with the basic plowing speed and drive wheel slip rate in the specified value or engine in the standard working condition, the maximum tractive force can be issued (take the smaller of the two values). Plowing is the most basic and heavy tractor operation in agricultural production, rated tractive force determination, the first should meet the plowing operation requirements.

$$F_g = zbhk, \tag{12}$$

where, F_g, plowing resistance; z, the number of plowshares, according to the selection of agricultural machinery, $z = 6$; b, the width of the single plowshare, $b = 0.45$m; h, plowing depth, $h = 0.25$m; k, soil specific resistance, take 7N/cm^2.

The driving resistance of the tractor will fluctuate due to changes in operating conditions and farm equipment, and should generally have a reserve tractive force of 10~20%. Therefore, the rated tractive force is:

$$F_T = (1.1 \sim 1.2)F_g. \tag{13}$$

3.2.2. Power System Matching Design

In conventional tractor design, the rated tractive force is used to determine the engine power. In the design of a Hybrid four-wheel drive tractor, the rear-drive system proposed in this paper can be considered as a traditional tractor engine for power selection compared to the traditional tractor engine power selection. And in the rear-drive system power distribution, the traditional parallel hybrid tractor compared to the traditional tractor in the structure of only a small power motor used to improve the power output of the engine, cannot play well with the electric drive system drive efficiency high environmental pollution low characteristics, in recent years with the development of electric drive system, electric drive system costs continue to reduce, so this paper uses a small power engine with high power electric motor. At the same time, in order to achieve a better anti-skid effect, the front-drive motor also uses a high-power motor.

Engine power:

$$P_e = \frac{0.65 \times F_T \times v_l}{3.6\eta_T}, \tag{14}$$

Rear-drive motor power:

$$P_{rm} = \frac{0.35 \times F_T \times v_l}{3.6\eta_T}, \tag{15}$$

Front-drive motor power:

$$P_{fm} = \frac{0.35 \times F_T \times v_l}{3.6\eta_T}, \tag{16}$$

where, v_l, the driving speed of the tractor during plowing operation, take 7 km/h; η_T, the efficiency of the transmission system, take 0.86.

In summary, the engine is an inline 4-cylinder supercharged inter-cooled high-pressure common rail diesel engine, model LR4A3LRP-T4-U3, with a rated power of 85 kw and rated speed of 2300 r/min. The rear-drive motor is a permanent magnet synchronous motor with a rated power of 45 kw, rated speed of 2500 r/min and rated voltage of 320 v. The front-drive motor is a Permanent magnet synchronous motor, its rated power is 45 kw, rated speed 2500 r/min, rated voltage 320 v.

3.2.3. Torque Coupler Design

For the selection of coupling device of parallel hybrid vehicle configuration, it can be divided into torque coupling type, speed coupling type, and power coupling type. Torque-coupled power sources are coupled in such a way that the output torques of the engine and motor are independent of each other, and the torque after coupling is the algebraic sum of the output torques of the two power sources. Speed coupling refers to the engine and motor power in the coupling, the two output speeds independent of each other, the final synthesis of the speed is a number of power sources each speed of the algebraic sum, and the output torque into a fixed proportion, the actual use of the tractor need to output a larger force, so the speed coupling for the tractor is not suitable for the design. Power-coupled engine and motor torque and speed are independent of each other, the output torque and output speed are the algebraic sums of the engine and motor [25], but the control system design is more complex. The torque-coupled type has a simple structure and the control system design is simple, so the torque-coupled type is used in this paper. The torque coupler is shown in Figure 2.

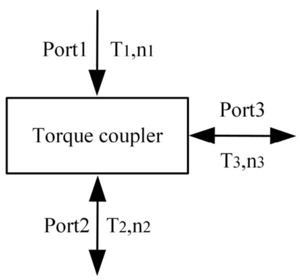

Figure 2. Torque coupler.

The torque coupler port 1 herein is a unidirectional torque and speed input, and ports 2 and 3 are bidirectional torque and speed inputs or outputs. In a hybrid tractor application, port 1 is connected to the engine via a transmission; port 2 is connected to the rear-drive motor via a transmission; and port 3 is connected to the drive wheels via a transmission.

4. Torque Distribution Control Strategy for Hybrid Four-Wheel Drive Tractor

The torque distribution control strategy of the Hybrid four-wheel drive tractor proposed in this paper includes the front- and rear-drive wheel torque distribution control strategy and the rear-drive system torque distribution control strategy, and the two torque distribution control strategies will be described separately below.

4.1. Front- and Rear-Drive Wheel Torque Distribution Control Strategy

From Formulas (2)–(4), the tractor in the plowing operation, plowing resistance, gradient resistance, and rolling resistance are important factors affecting the drive wheel slip rotation, air resistance and acceleration resistance value is small, neglected. Therefore, the concept of road resistance coefficient is introduced, the road resistance coefficient is the sum of the gradient and rolling resistance coefficient, and it can reflect the road resistance situation. The tractor's drive wheel slip rate is controlled at about 10~15%, and the tractor has the highest traction efficiency.

During tractor plowing, the tractor center of mass will move backwards, the tractor axle load distribution will change, the rear axle load will become larger, and the rear-drive wheel rolling resistance will also become larger. The change in rear-drive wheel rolling resistance will have an effect on the distribution of tractive force between the front- and rear-drive wheels of the tractor. From the joint simulation data of AVL-CRUISE and MATLAB/Simulink, the real-time rolling resistance of the rear-drive wheel and the real-time axle load distribution of the tractor are obtained, and the rolling resistance coefficients of the front-drive wheel, the rear-drive wheel and the whole vehicle are calculated. Comparing each rolling resistance coefficient, it can be seen that the rear-drive wheel rolling resistance coefficient is larger than the whole vehicle rolling resistance coefficient than the front-drive wheel rolling resistance coefficient. The rear-drive wheel of the tractor carries more tractive force compared with the front-drive theory, so the rear-drive wheel rolling resistance coefficient is substituted into the calculation of road resistance coefficient, which can better reflect the resistance of the tractor.

The tractor operating conditions are complex and variable, and it is known from Formulas (10) and (11) that there is a high degree of nonlinearity between the tractor's front-drive wheel tractive force, rear-drive wheel tractive force, and tractive force distribution coefficient k. The fuzzy controller has a better control effect for the nonlinear system. The plowing resistance and road resistance coefficient are selected as the input variables of the fuzzy controller, and the tractive force distribution factor k is selected as the output variable of the fuzzy controller.

The front- and rear-torque distribution control strategy of a Hybrid four-wheel drive tractor is shown in Figure 3. In order to verify the superiority of the front- and rear-drive wheel torque distribution control strategy based on fuzzy control proposed in this paper, the front- and rear-torque distribution control strategy based on fixed ratio distribution is set as the comparison control strategy, and the front- and rear-torque distribution control strategy based on fixed ratio distribution is shown in Figure 4.

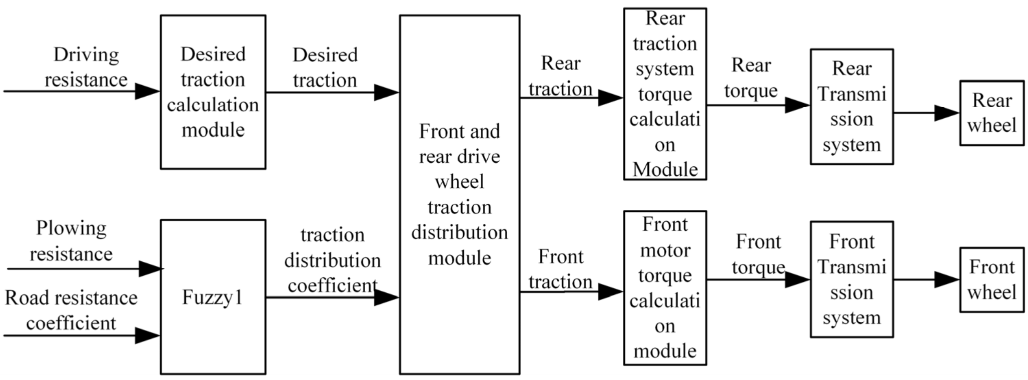

Figure 3. Control strategy for torque distribution of front- and rear-drive wheels based on fuzzy control.

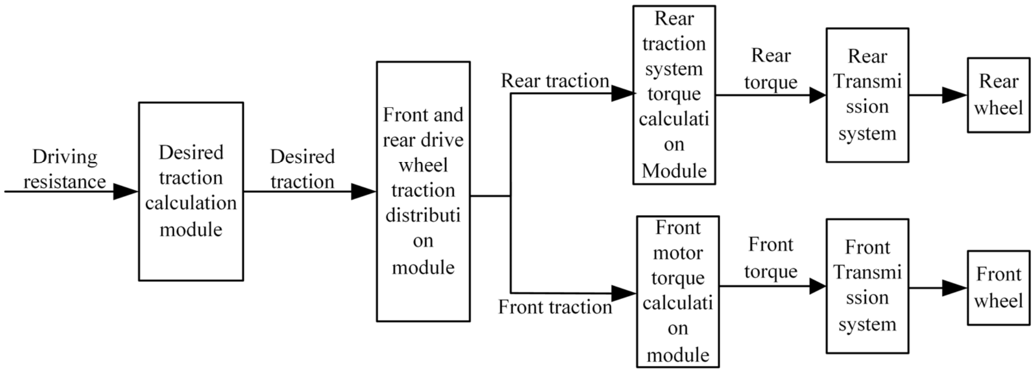

Figure 4. Control strategy for torque distribution of front- and rear-drive wheels based on fixed ratio distribution.

In Figure 3, the AVL-CRUISE software inputs the driving resistance and outputs the desired tractive force through the desired tractive force calculation module. The plowing resistance and road resistance coefficient are used as input variables of fuzzy controller 1, and the output variable tractive force distribution coefficient k is obtained by fuzzification, fuzzy inference and anti-fuzzification of fuzzy controller 1, and then the k value is transmitted to the front- and rear-drive wheel tractive force distribution module. The front- and rear-drive wheel tractive force distribution module distributes the tractive force of the front-drive wheel and the rear-drive wheel through the demand tractive force and the tractive force distribution coefficient. The front-drive wheel tractive force and rear-drive wheel tractive force are calculated to obtain the front-drive system torque and rear-drive system torque, which are transmitted to the front-drive wheels and rear-drive wheels through the transmission system. In Figure 4, the torque distribution control strategy based on fixed ratio distribution is the same as the strategy proposed in this paper except that the tractive force distribution coefficient is different from the strategy proposed in this paper.

4.1.1. Affiliation Function Design

The exact values of plowing resistance were converted into proportional values with the theoretical domain of [0.8, 1] for plowing resistance, [−0.05, 0.22] for road resistance coefficient, and [0.12, 0.22] for tractive force distribution coefficient.

The formula for converting the exact value of plowing resistance into a proportional value is:

$$F_{gp} = \frac{F_g}{F_{g\max}}, \tag{17}$$

where, F_{gp}, the proportional value of the plowing resistance; F_g, the plowing resistance at a certain moment; $F_{g\max}$, the maximum value of the plowing resistance.

And, respectively, stipulate the following fuzzy subsets: the fuzzy subset of proportional values of plowing resistance is E(F) = {NB,NM,Z,PM,PB}. The fuzzy subset of road resistance coefficient is E(R) = {NH,NL,Z,PL,PH}. The fuzzy subset of the tractive force distribution coefficient is E(k) = {ND,NB,NM,NS,Z,PS,PM,PB,PD}. The fuzzy subsets {NH,NL,Z,PL,PH} represent negative high, negative low, medium, positive low, and positive high, respectively. The fuzzy subsets {ND,NB,NM,NS,Z,PS,PM,PB,PD} represent negative pole, negative large, negative medium, negative small, medium, positive small, positive medium, positive large, and positive pole, respectively.

In summary, the affiliation function of plowing resistance is shown in Figure 5, the affiliation function of road resistance coefficient is shown in Figure 6, and the affiliation function of tractive force distribution coefficient is shown in Figure 7.

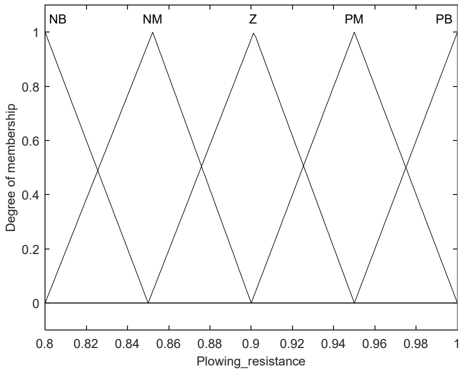

Figure 5. Affiliation function of plowing resistance.

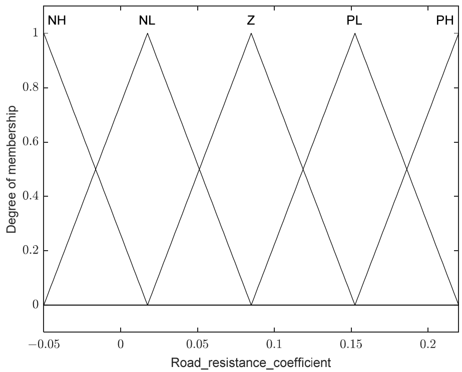

Figure 6. Affiliation function of road resistance coefficient.

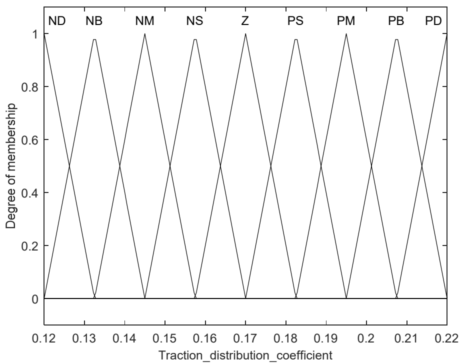

Figure 7. Affiliation function of tractive force distribution coefficient.

4.1.2. Fuzzy Rules Design

The design of fuzzy rules needs to fully consider the operating conditions of the tractor, the design of fuzzy rules as shown in Table 1.

Table 1. Fuzzy control rules library.

k		**Plowing Resistance**				
		NB	NM	Z	PM	PB
Road resistance coefficient	NH	ND	ND	ND	NB	NM
	NL	ND	NB	NM	NS	Z
	Z	NM	NS	Z	PS	PM
	PL	Z	PS	PM	PB	PD
	PH	PS	PM	PB	PD	PD

where, *k*, tractive force distribution coefficient.

4.2. Control Strategy for Torque Distribution of Rear-Drive System

The torque distribution of the parallel hybrid tractor is highly nonlinear, and the fuzzy control strategy is well suited for the hybrid tractor control system. The rear-drive system desired torque and battery SOC are used as input variables, and the motor torque distribution coefficient is used as the output variable to establish the fuzzy control-based rear-drive system torque distribution control strategy. The rear-drive system torque distribution control strategy is shown in Figure 8.

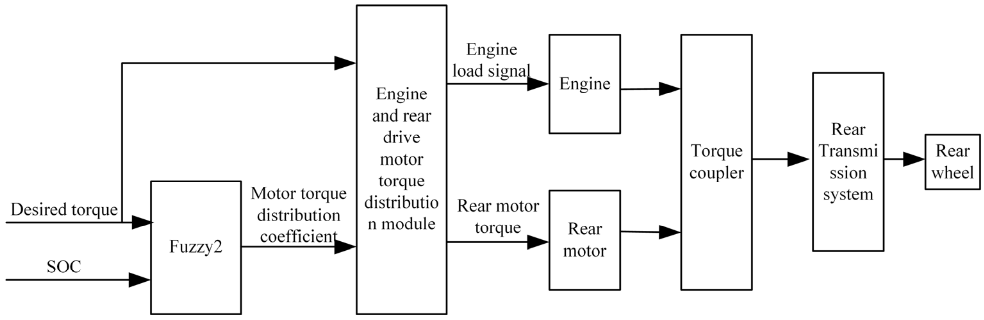

Figure 8. Control strategy for torque distribution of rear-drive system.

4.2.1. Affiliation Function Design

The exact value of the desired torque of the rear-drive system is converted into a proportional value, and the domain of the desired torque of the rear-drive system is [0, 1], the domain of the battery SOC is [0, 1], and the domain of the motor torque distribution coefficient is [−0.2, 1].

Motor torque distribution coefficient is the ratio of the rear motor torque to the desired torque of the rear-drive system.

$$\lambda = \frac{T_m}{T_r}, \tag{18}$$

where, T_r, the desired torque of the rear-drive system at a certain moment; T_m, rear motor torque; λ, motor torque distribution coefficient.

The formula for converting the exact value of the desired torque of the rear-drive system into a proportional value is:

$$T_{rp} = \frac{T}{T_{\max}}, \tag{19}$$

where, T_{rp}, the proportional value of the desired torque of the rear-drive system; $T_{\max}$, the maximum desired torque of the rear-drive system.

And, respectively, stipulate the following fuzzy subsets: E(T_{rp}) = {NB,NM,Z,PM,PB}, E(SOC) = {NH,NL,Z,PL,PH}, E(λ) = {TS,S,M,B,TB}. The fuzzy subsets {NB,NM,Z,PM,PB} represent negative large, negative medium, medium, medium, and large, respectively. The fuzzy subsets {NH,NL, Z,PL,PH}stand for negative high, negative low, medium, positive low, and positive high, respectively. Fuzzy subsets {TS,S,M,B,TB} represent very small, small, medium, large, and very large, respectively.

In summary, the affiliation function of the desired torque is shown in Figure 9, the affiliation function of the SOC is shown in Figure 10, and the affiliation function of the motor torque distribution coefficient is shown in Figure 11.

4.2.2. Fuzzy Rules Design

The design of fuzzy rules needs to fully consider the operating characteristics of the parallel hybrid configuration. The designed fuzzy rules are shown in Table 2.

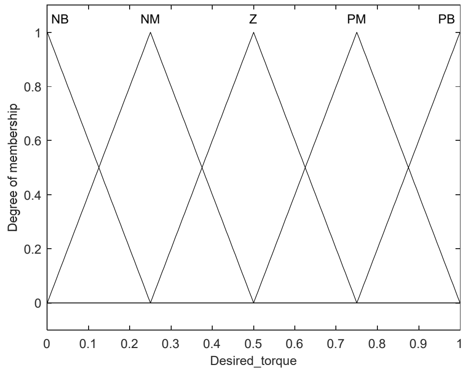

Figure 9. Affiliation function of desired torque.

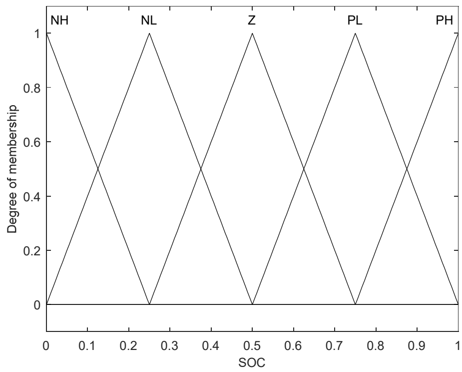

Figure 10. Affiliation function of SOC.

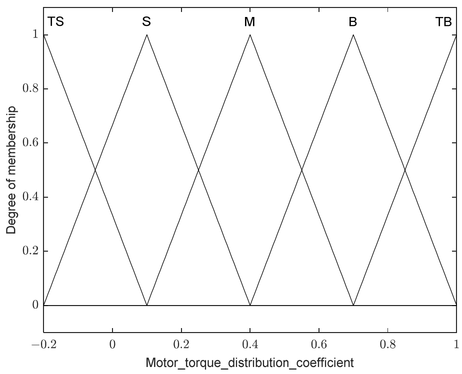

Figure 11. Affiliation function of motor torque distribution coefficient.

Table 2. Fuzzy control rules library.

λ		Desired Torque				
		NB	NM	Z	PM	PB
SOC	NH	TS	TS	S	S	M
	NL	TS	S	S	M	M
	Z	S	S	M	B	B
	PL	TB	B	B	M	B
	PH	TB	TB	B	M	B

where, λ, motor torque distribution coefficient.

5. Comparative Analysis

In this paper, AVL-CRUISE software is used to establish a vehicle model of a Hybrid four-wheel drive tractor [26–28], the main technical parameters of the Hybrid four-wheel drive tractor are shown in Table 3, and MATLAB/Simulink software is used to build a torque distribution control strategy based on fuzzy control, and the joint simulation analysis of AVL-CRUISE and MATLAB/Simulink is carried out.

Table 3. Hybrid four-wheel drive tractor main technical parameters.

Project	Parameter	Value
Vehicle	Quality/kg Wheel base/mm	7350 2800
Engine	Rated power/kw Rated speed/(r/min)	85 2300
Front motor	Rated power/kw Rated speed/(r/min)	45 2500
Rear motor	Rated power/kw Rated speed/(r/min)	45 2500
Gearbox	4th gear transmission ratio	3.6
Front final reduction drive	transmission ratio	5.5
Rear final reduction drive	transmission ratio	5.0

The vehicle model of the Hybrid four-wheel drive tractor built by AVL-CRUISE software is shown in Figure 12. The force1 module and force2 module in the figure are the two sets of plowing resistance modules established.

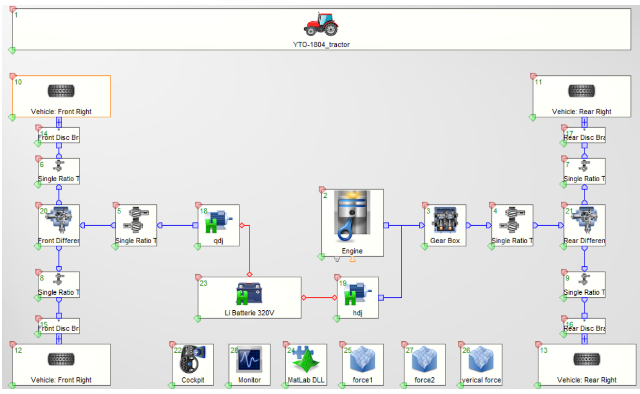

Figure 12. Hybrid four-wheel drive tractor vehicle model.

The torque distribution control strategy based on fuzzy control established by MATLAB/Simulink software is shown in Figure 13.

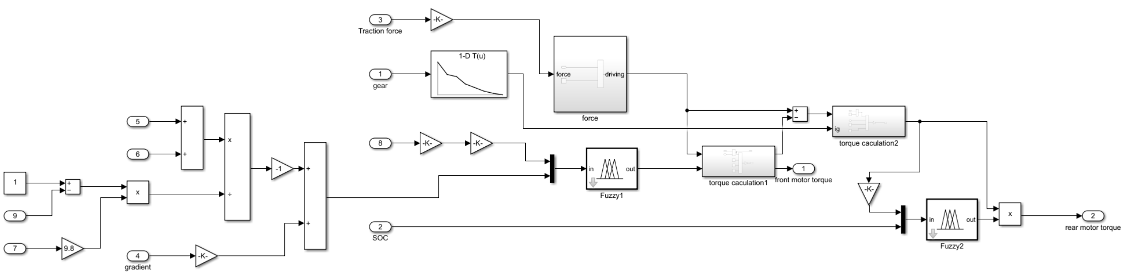

Figure 13. Torque distribution control strategy based on fuzzy control.

When the tractor is actually working, the resistance of different operating conditions is different. According to different operating conditions, tractor operation mode can be divided into three: heavy load mode (80% of the rated tractive effort above), medium load mode (about 20% to 80% of the rated tractive effort), and light load mode (20% of the rated tractive effort below). Tractor plowing working condition operation, resistance is higher, belong to the heavy load mode.

The actual plowing operation of the tractor is mostly flat, and the gradient is generally less than 10%. In order to fully verify the effect of the two torque distribution control strategies on the performance of the Hybrid four-wheel drive tractor, a certain road gradient was set along with the plowing resistance. Considering the effect of rolling friction resistance and gradient resistance set plowing resistance. At the same time, in order to verify the effect of two torque distribution control strategies on the working stability of a Hybrid four-wheel drive tractor set two groups of plowing resistance, one group for small plowing resistance group, and one group for large plowing resistance group.

The established small plowing resistance group is shown in Figure 14 and the established large plowing resistance group is shown in Figure 15.

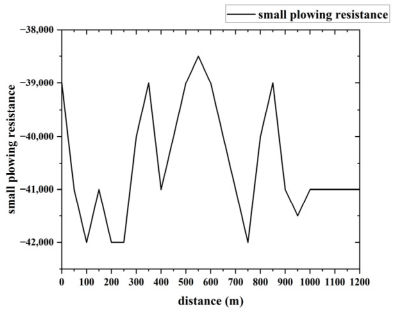

Figure 14. Small plowing resistance.

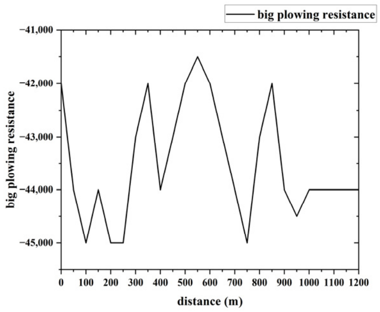

Figure 15. Big plowing resistance.

The set road slope is shown in Figure 16.

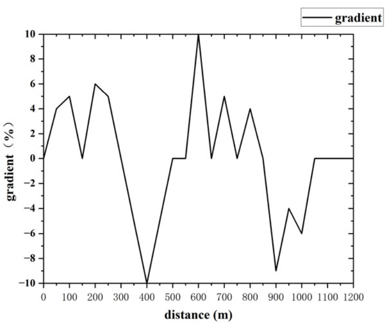

Figure 16. Gradient.

As shown in Figures 17 and 18, when the Hybrid four-wheel drive tractor was loaded with a small plow resistance group, the fuzzy control-based torque distribution control strategy reduced the tractor rear wheel slip rate by 4.5% on average and the maximum slip rate by 18.7% compared to the fixed ratio-based torque distribution control strategy. The fuzzy control-based torque distribution control strategy can basically control the rear-drive wheel slip rate in the range of 10% to 15%, and the variance of the rear-drive wheel slip rate is only 1.16 for the fuzzy control-based torque distribution control strategy and 3.87 for the fixed ratio-based torque distribution control strategy, which shows that the fuzzy control strategy based torque distribution control strategy can not only control the rear-drive wheel slip rate. This shows that the torque distribution control strategy based on the fuzzy control strategy can not only control the slip rate of the rear-drive wheel at 10%~15%, but also the slip rate fluctuation is small, and the Hybrid four-wheel drive tractor can obtain high traction efficiency. At the same time, the fuzzy control-based torque distribution control strategy has a small difference in the slip rate of the front-drive wheel compared to the fixed ratio-based torque distribution control strategy.

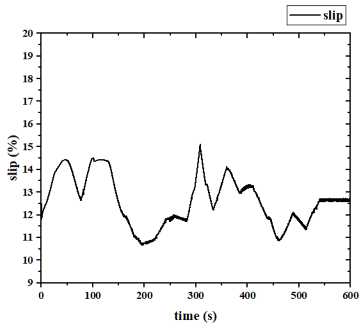

Figure 17. Slip rate of rear-drive wheels with fuzzy control.

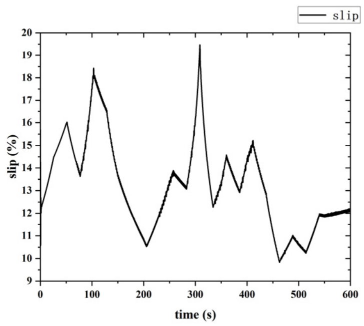

Figure 18. Slip rate of rear-drive wheels with fixed ratio distribution.

When the Hybrid four-wheel drive tractor is loaded with a large plowing resistance group, as shown in Figure 19, the Hybrid four-wheel drive tractor with fuzzy control-based torque distribution control strategy can complete the operation task, and as shown in Figure 20, the Hybrid four-wheel drive tractor with fixed ratio distribution based torque distribution control strategy cannot complete the operation, which shows that the Hybrid four-wheel drive tractor with fuzzy control-based torque distribution control strategy has better adaptability to the working conditions and can cope with the complex agricultural production environment.

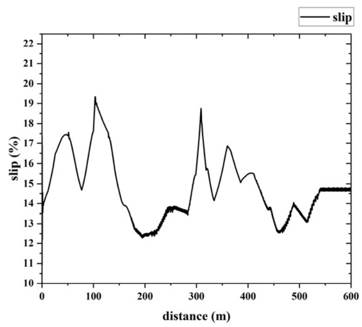

Figure 19. Slip rate of rear-drive wheels with fuzzy control.

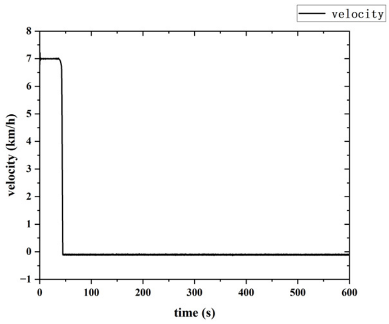

Figure 20. Tractor velocity with fixed ratio distribution.

Through the comparative analysis of two torque distribution control strategies, it can be seen that the fuzzy control-based torque distribution control strategy can significantly reduce the drive wheel slip rate, and the Hybrid four-wheel drive tractor can obtain higher traction efficiency. And good adaptability to working conditions, more widely used.

The rear-drive system adopts the fuzzy control-based torque distribution control strategy, based on the analysis of the tractor plowing conditions, as shown in Figure 21, the tractor plowing operation engine speed fluctuations are not large, smooth operation, while the engine torque in the engine high efficiency torque operating range, the economy is better.

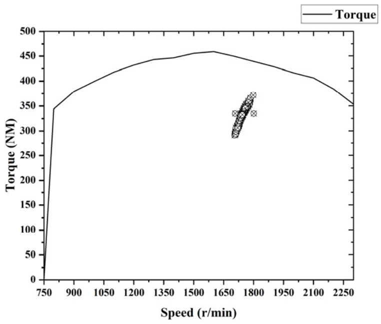

Figure 21. Engine working point distribution map.

6. Conclusions

(1). By analyzing the defects of the existing tractor power system, this paper, a Hybrid four-wheel drive tractor is proposed, and the parameters of the main components are calculated and matched, while a torque distribution control strategy is developed.

(2). The vehicle model of the Hybrid four-wheel drive tractor was established in AVL/CRUISE software, and the vehicle torque distribution control strategy based on fuzzy control and the vehicle torque distribution control strategy based on fixed ratio distribution were established in MATLAB/SIMULINK software. The joint simulation was carried out with the tractor's plowing operation as an example.

(3). The simulation results show that the fuzzy control-based front- and rear-drive wheel torque distribution control strategy can control the slip rate of the tractor rear-drive wheel at 10%~15% compared with the fixed ratio distribution based front- and rear-drive wheel torque distribution control strategy, the average slip rate of the tractor rear wheels has been reduced by 4.5%, the maximum slip rate of the rear-drive wheels has been reduced by 18.7%, and the variance has been reduced by 70%, and the traction performance has been greatly improved.

(4). The simulation results show that when the Hybrid four-wheel drive tractor was loaded with a large plowing resistance group, the Hybrid four-wheel drive tractor with the fuzzy control-based front- and rear-drive wheel torque distribution control strategy was able to complete the operation, and the Hybrid four-wheel drive tractor with the fixed ratio distribution based front- and rear-drive wheel torque distribution control strategy was not able to complete the operation. The results show that the Hybrid four-wheel drive tractor with fuzzy control-based front- and rear-drive wheel torque distribution control strategy has better adaptability to working conditions and can cope with complex agricultural production environments.

(5). The simulation results show that the established torque distribution control strategy for the rear-drive system is able to control the engine operating point within the period of efficient engine operation with better economy.

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