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Research on Wet Clutch Switching Quality in the Shifting Stage of an Agricultural Tractor Transmission System

Yuting Chen [1], Zhun Cheng [1,*] and Yu Qian [2]

[1] Department of Vehicle Engineering, Nanjing Forestry University, Nanjing 210037, China
[2] College of Engineering, Nanjing Agricultural University, Nanjing 210031, China
* Correspondence: cz38@njfu.edu.cn

Abstract: In order to improve the working quality of wet clutch switching in an agricultural tractor, in this paper, we took a power shift system composed of multiple wet clutches as the research object for full-factorial performance measurement, multi-factor analysis of the degree of influence, establishment of a single evaluation index model, formation of a comprehensive evaluation index, and formulation of adjustable factor control strategies. We studied the simulation test platform of an agricultural tractor power transmission system based on the SimulationX software and obtained 225 sets of sample data under a full-use condition. Partial least squares and range analysis were applied to comprehensively analyze the influence of multiple factors on the working quality of wet clutches. In this paper, we proposed a modeling method for a single evaluation index of the wet clutch (combined with polynomial regression and tentative method, the goal is determined in the form of a model with the maximum coefficient of determination) and two control strategy optimization methods for the wet clutch adjustable factors, i.e., Method 1 (integrated optimization) and Method 2 (step-by-step optimization), both methods were based on an improved genetic algorithm. The results showed that oil pressure, flow rate, and load had significant effects on the dynamic load characteristics (the degrees were 0.38, −0.44, and −0.63, respectively, with a negative sign representing an inverse correlation); rate of flow and load had significant effects on speed drop characteristics (the degrees were −0.56 and 0.73, respectively). A multivariate first-order linear model accurately described the dynamic load characteristics (R^2 = 0.9371). The accuracy of the dynamic load characteristic model was improved by 5.5037% after adding the second-order term and interaction term of oil pressure. The polynomial model containing the first-order oil pressure, first-order flow rate, second-order flow rate, and interaction terms could explain the speed drop characteristics, with an R^2 of 0.9927. If agricultural tractors operate under medium and large loads, the oil pressure and flow rate in their definitional domains should be small and large values, respectively; if operating under small loads, both oil pressure and flow rate should be high. When the wet clutch dynamic load and speed drop characteristics were improved, the sliding friction energy loss also decreased synchronously (the reduction could reach 70.19%).

Keywords: simulation; quality improvement; improved genetic algorithm; full-factorial test; single evaluation index modeling method; control strategy

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1. Introduction

A tractor is a widely used vehicle in agricultural operations [1–3], which has some differences in driving speed and load when performing ploughing, rotary tillage, or transportation tasks [4]. Therefore, there are clear requirements for the coordination of the power source and transmission system when operating agricultural tractors. Regarding power sources, an agricultural tractor is similar to road driving vehicles, mainly using a "power battery [5,6] motor [7–9] system" or an internal combustion engine system [10]. The combined use of a variable speed transmission system can further improve the working performance of an agricultural tractor (mainly the power performance and economic performance).

A transmission gearbox is the core device of a vehicle transmission system that changes the transmission ratio to achieve acceleration and torque reduction or deceleration and increased torque. The advanced variable speed transmission systems in agricultural tractors (these new systems are formed based on the development of computer technology, electronic control technology, and hydraulic technology [11]) are mainly composed of power shift transmissions [12,13] and power-split continuously variable transmissions (CVT) [14,15]. These advanced transmission systems can change their operating mode when changing transmission ratios. During the process of changing the operating mode, there is a need for a reliable mechanical system with a smooth switching process, and the power cannot be interrupted during the switching process. To meet the above requirements, wet clutches are widely used in the advanced transmission systems of agricultural tractors to achieve transmission gearbox switching [16].

At present, there is increased interest in research on agricultural tractor wet clutches. Cheng et al. [17,18], Sun et al. [19], and Li et al. [20] have conducted corresponding design, parameter matching, and performance analyses of a tractor with hydraulic mechanical continuously variable transmission (HMCVT) and wet clutches. Current research on wet clutches has focused on improving clutch performance, specifically, mainly including a wet clutch working quality analysis and control strategy formulation. For example, Qian et al. [21] conducted an orthogonal test with five factors and four levels, combined with the SimulationX software and stepwise regression to study the shift quality of wet clutches of heavy tractors. They developed a mathematical model of wet clutch performance based on an oil pressure domain of 2~6 MPa, a flow domain of 3~6 L/min, and a load torque domain 200~641 Nm. Ni et al. [22] also used an orthogonal test with five factors and four levels (but the factors and levels were different from that of the Qian et al. [21] study) combined with a bench test. They conducted 16 trials and used range analysis to obtain the optimal oil pressure and flow during clutch operation. Wang et al. [23] conducted an orthogonal test with four factors and three levels and a single-factor test and mainly relied on the analysis of variance and a range analysis. Stockinger et al. [24] analyzed the friction performance of a multiple sheet wet clutch. The research of Raikwar et al. [25] mainly used the MATLAB software to build a tractor vehicle simulation model, including a wet clutch model and analyzed smooth clutch engagement, reduced transmission shock, and operator discomfort.

Overall, currently, the number of studies on wet clutches in agricultural tractors is relatively small. The existing studies have mainly conducted simulation tests or actual tests. However, most of the studies have had a relatively small number of trial samples. Most studies have explored the scheme of improving the working quality of a wet clutch by means of an orthogonal test combined with the analysis of variance or a range analysis. However, it is difficult to apply these methods for in-depth analyses. In addition, most studies have tended to use the revolution or load torque working conditions of an agricultural tractor as a factor in orthogonal tests. However, in fact, agricultural tractors can or need to work under varied working conditions. Therefore, it is much more important to study the switching quality of agricultural tractors under different working conditions. There is a lack of research on evaluation index modeling related to the switching quality of a wet clutch under the full-use conditions of an agricultural tractor.

To solve the abovementioned problems, in this paper, we have focused on five parts (full factorial simulation tests, analysis of the degree of influence of factors, model establishment of a single evaluation index, model establishment of a comprehensive evaluation index, and control strategy optimization and formulation). The value and innovation of this research include: Relatively large sample data are used to investigate the working quality of an agricultural tractor wet clutch; partial least squares, a range analysis, polynomial regression, analytic hierarchy process, and the heuristic intelligent optimization algorithm are comprehensively used for systematic research and analysis; two optimization and formulation methods for the wet clutch control strategies for an agricultural tractor under full-use conditions are proposed; the modeling method of a work quality evaluation index model is proposed. In this paper, we provide a basis and valuable reference for the design, performance evaluation, performance estimation, control, and performance improvement of a wet clutch for agricultural machinery.

2. Materials and Methods

2.1. Agricultural Tractor Transmission System with Wet Clutch

In this paper, we studied an advanced transmission system for an agricultural tractor. See Figure 1 for the transmission scheme. The transmission system is a hydraulic mechanical CVT (HMCVT). It has five working segments, and each working segment can realize the continuous change of its own transmission ratio within a certain range.

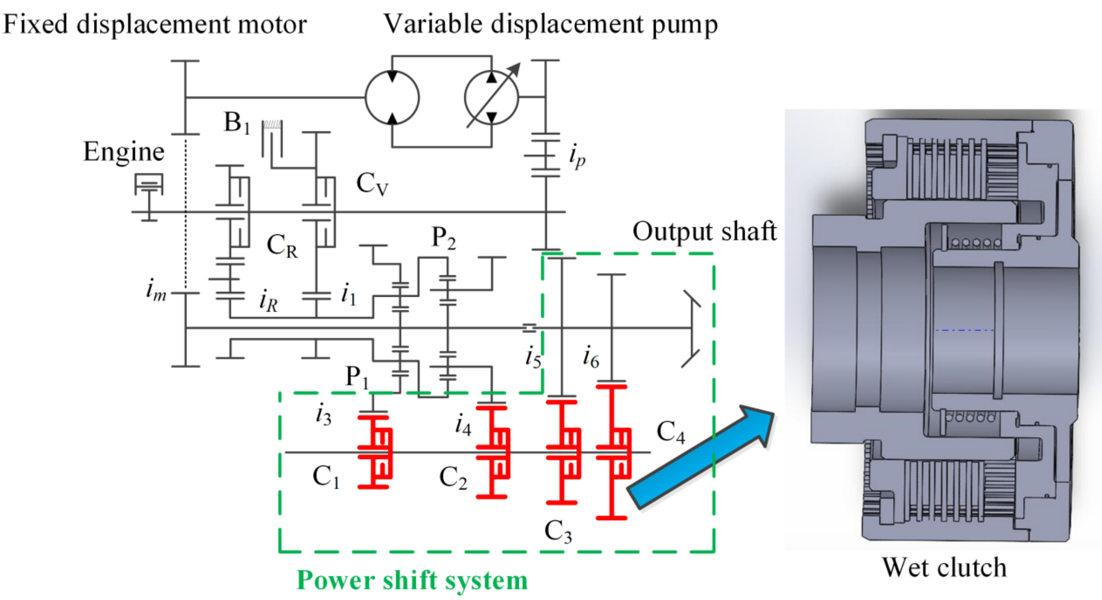


Figure 1. HMCVT for agricultural tractors, as studied in the paper.

The "power shift system" shown in Figure 1, can also be a core device for other types of power shift transmission for agricultural tractors. Therefore, in this paper, we focused on a hydraulic and mechanical power shunt CVT transmission, and also on a power shift transmission.

The HMCVT mainly consisted of two planetary gear devices (P_1 and P_2), six wet clutches (C_V, C_R, C_1, C_2, C_3, and C_4), one brake (B_1), one pump-motor system (the working mechanism involved a variable pump that controlled the quantitative motor to change the revolution of the motor output shaft), and multiple fixed gears (the gear secondary transmission ratio was set to i_1, i_R, i_3, i_4, i_5, i_6, i_p, and i_m respectively). The working parameters and working principles of the system were referred to in a previous study [18].

2.2. Wet Clutch Switch Simulation Test Platform Based on the SimulationX Software

Simulation is a core technology that is widely used in engineering research. Simulation results in a variety of engineering fields have been verified for their accuracy and effectiveness (for example, the research works of Talati et al. [26], Torshizian et al. [27], Aliakbari et al. [28], etc.). The SimulationX software has been verified by several previous studies in clutch performance simulation tests (for example, Lu et al. [29] showed that the maximum error of the simulation test results of the wet clutch and the actual test results did not exceed 6%, and the average error did not exceed 5%; Wang et al. [30] showed that the relative error of the simulation test results of the wet clutch and the actual test results was less than 10%.).Therefore, in this paper, we studied various models built using the SimulationX software to build the HMCVT gear switching simulation test platform and used the abovementioned studies in the literature as references (see Figure 2 for the schematic diagram of the simulation test platform). The simulation test platform mainly included a pump-motor system model (the pump was a variable pump, and its displacement ratio was adjustable), a fixed shaft gear model, a motor model, a load simulation model, a wet clutch model, a clutch oil filling pressure simulation model, and a planetary gear model.

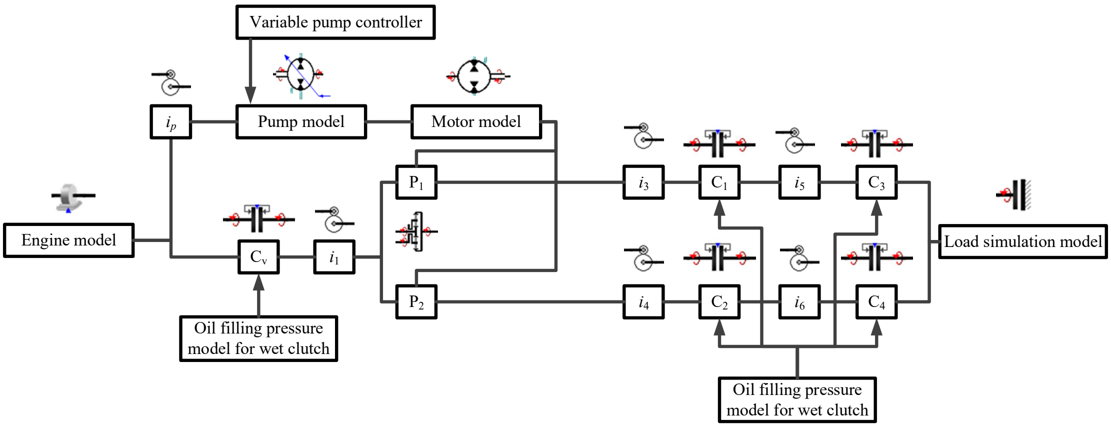


Figure 2. Schematic diagram of the simulation test platform used in this paper.

2.3. Full-Factorial Test Design under Full-Use Conditions of Agricultural Tractors

The goal of this research was to explore the performance change characteristics of a wet clutch when the power shift transmission of an agricultural tractor was shifted under various operating conditions. The optimal control strategies of oil pressure and flow rate were formulated for optimal working quality of the clutch. Therefore, in this paper, we took the switch of an HM1 segment bit to HM2 segment bit in a five-segment HMCVT as an example. During the gear switch, the C_2 wet clutch was disconnected and the C_1 wet clutch combined.

In this paper, the total mass of the agricultural tractor was set to be 3000 kg; the working revolution range of the diesel engine was 800–2200 rpm; the radius of the driving wheel was 0.976 m, and the rolling resistance coefficient was assumed to be 0.2. The maximum load condition of the agricultural tractor was the plough industry condition. The plough resistance of an agricultural tractor is usually estimated using the following formula [31]:

$$F_p = r_1 zbhk \tag{1}$$

where r_1 is the instability coefficient, which is used to characterize fluctuations in the plowing resistance when an agricultural tractor is ploughing in a field; z is the number of ploughshares, and the value in this study is 5; b is the tillage width of a single plough body, which is 40 cm in this study; h is the tillage depth, which is 18 cm in this study; k is the soil specific resistance, which is 60 kPa in this study.

Since agricultural tractors travel slowly when plowing, in this study, the air resistance of the agricultural tractor was ignored. The load resistance torque at the output end of the agricultural tractor transmission is (refer to vehicle driving resistance equation [32]):

$$T_{out} = (F_p + F_f)r_d / i_0 = (F_p + mgf)r_d / i_0 \tag{2}$$

where T_{out} is the load resistance torque at the output end of the transmission; F_f is the rolling resistance of the agricultural tractor; m is the total mass of the agricultural tractor; g is the acceleration of gravity; f is the rolling resistance coefficient; r_d is the driving force radius; i_0 is the total gear ratio of the drive train, excluding the transmission.

Combining Equations (1) and (2), it could be calculated that the maximum load resistance torque at the output end of the agricultural tractor transmission was about

1000 Nm. Therefore, the full-use conditions of the agricultural tractor studied in this paper were: the working revolution of the engine varied from 800 to 2200 rpm (that is, the working revolution of the input end of the transmission varied from 800 to 2200 rpm); the load torque variation range of the transmission output end was 0~1000 Nm.

In this paper, the working revolution of the input end and the output end load torque of the HMCVT were divided into three levels in their respective definition domains. Atotal of nine use conditions for an agricultural tractor were studied in this paper (see Table 1).

Table 1. Factor level combination of the agricultural tractor full-use conditions.

HMCVT Output Load Torque Nm	HMCVT Input Working Revolution rpm		
	800	1500	2200
200	Low speed small load	Medium speed small load	High speed small load
600	Low speed medium load	Medium speed medium load	High speed medium load
1000	Low speed large load	Medium speed large load	High speed large load

Under the working conditions, the working parameters (oil filling pressure and filling flow) of the wet clutches were divided into five levels within their respective domain range. Then, the horizontal combination of oil pressure was 2, 3, 4, 5, and 6 MPa; the horizontal combination of flow was 2, 3, 4, 5, and 6 L/min. Therefore, 25 sets of simulation tests were required for each working condition of the agricultural tractor. In summary, the number of full-factorial test groups used in this study was 225.

2.4. Analysis Method for the Degree of Influence of Working Condition Factors and Adjustable Factors

In this paper, the working revolution of the HMCVT input end and the output end load torque were the working condition factors studied, that is, the agricultural tractor always worked at a certain revolution and torque working conditions.

The oil filling pressure and flow rate of a wet clutch were the adjustable factors studied, that is, the operation of the agricultural tractor could be adjusted and controlled under any working condition.

We used partial least squares (PLS) [33,34] and a range analysis (RA) [35] to analyze the degree of influence of factors (including working conditions and adjustable factors) for the results of the full-factorial tests.

The calculation formula for the range differential analysis is as follows [35]:

$$R_i = \max(\overline{X}_i) - \min(\overline{X}_i) \tag{3}$$

where R_i is the range of the i_{th} factor, $\overline{X}_i$ is the set of sample data means of all levels of the i_{th} factor.

The analysis process for the degree of influence of factors used in this study is as follows:

Step 1. Calculate and analyze the degree of influence for 225 sets of test results on working condition factors (HMCVT input working speed and output load torque) by using PLS and RA, respectively.
Step 2. Calculate and analyze the degree of influence for 225 sets of test results on working condition factors (oil filling pressure for wet clutch) by using PLS and RA, respectively.
Step 3. Compare the analysis results of the PLS and RA, and draw common conclusions.

2.5. Selection of a Single Evaluation Index and the Model-Building Method

There were a number of indicators in the performance evaluation of the wet clutches, among which the most important were the evaluation indicators related to the output end speed and torque. The wear dissipation energy (i.e., sliding friction work) was an-other important physical quantity. The calculation formula of sliding friction work is as follows [30]:

$$W_c = \int_{t_1}^{t_2} T_c(t)|\Delta\omega(t)|dt \quad (4)$$

where W_c is the energy loss of sliding friction, t_1 is the start time of clutch engagement, t_2 is the end time of clutch engagement, $T_c(t)$ is the torque transmitted by the clutch, $\Delta\omega(t)$ is the revolution difference between the master and driven ends of the clutch.

From Equation (4), the evaluation indicators related to the revolutions and torque also had the ability to reflect the sliding friction size during the wet clutch bonding process. Therefore, in this paper, the physical quantity related to the output end revolutions and the torque was selected as the evaluation index, including the speed drop and the dynamic load, respectively.

The speed drop formula is calculated as follows [30]:

$$J = |\omega_\infty - \omega_{\min}| \quad (5)$$

where J is the speed drop, which is dimensionless; ω_∞ is the output revolution of the transmission in steady state after shifting; $\omega_{\min}$ is the minimum output revolution of the transmission during the clutch switching process.

The formula of the dynamic load is as follows [30]:

$$K = T_{c\_\max}/T_\infty \quad (6)$$

where K is the dynamic load, dimensionless; $T_{c\_\max}$ is the maximum torque at the output end of the transmission during the clutch switching process; T_∞ is the output torque in the steady state after the transmission is shifted, and this physical quantity is basically determined by the output end load.

Polynomial regression models are widely used in the engineering field. In this paper, we proposed a polynomial regression-based modeling method for wet clutch performance evaluation indicators (speed drop and dynamic load). This method combined the observation of 225 sets of full-factorial simulation test data and used the tentative method of a heuristic intelligent optimization algorithm (such as the artificial fish school algorithm). For the full working conditions of the simulation test, the estimation model of the evaluation index (speed drop and dynamic load) was determined by testing several types of polynomial models and taking the maximum target of the coefficient. The test process took the multivariate first-order linear regression model as the first test model, and then added the second-order terms and interaction terms of each independent variable one by one to form a new test model. The final model form was determined by comparing the dependent coefficients of the previous and the subsequent tentative model. A flow chart of this modeling method is presented in Figure 3.

2.6. Method for Establishing a Comprehensive Evaluation Index of Wet Clutch Working Quality

In this paper, the weighting coefficient method was used to establish a comprehensive evaluation index by combining two single evaluation indexes (speed drop and dynamic load). According to the literature [36], the analytic hierarchy process (AHP) was used to determine the weighting coefficient of two single evaluation indexes (i.e., speed drop and dynamic load). The mathematical expression of the comprehensive evaluation index is as follows:

$$CEI = w_1 K/K_{\max} + w_2 J/J_{\max} \quad (7)$$

where CEI is the comprehensive evaluation index of the working quality of the wet clutch; w_1 and w_2 are the weighting coefficients of dynamic load and speed drop, respectively, while $w_1 + w_2 = 1$; $K_{\max}$ and $J_{\max}$ are the maximum values of dynamic load and speed drop in the test sample data, respectively. In this way, the original index was converted into a dimensionless index to assimilate the order of magnitude of the two single evaluation indexes.

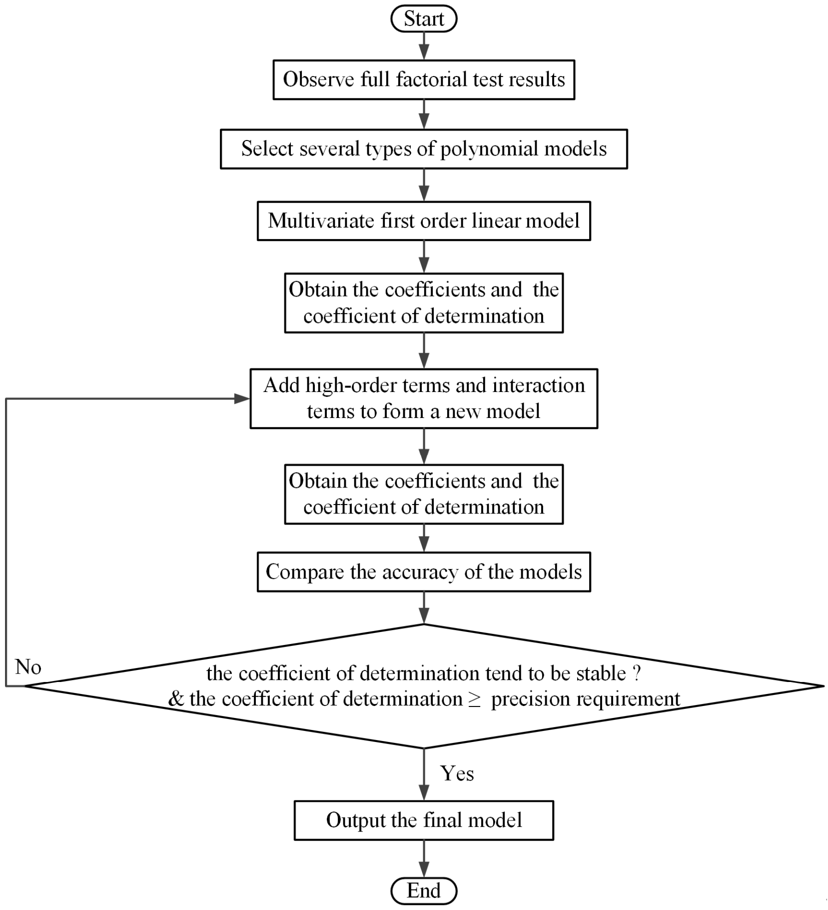


Figure 3. Flow chart of the performance evaluation index modeling method proposed in this paper.

The layers of the wet clutch switching quality are shown in Figure 4.

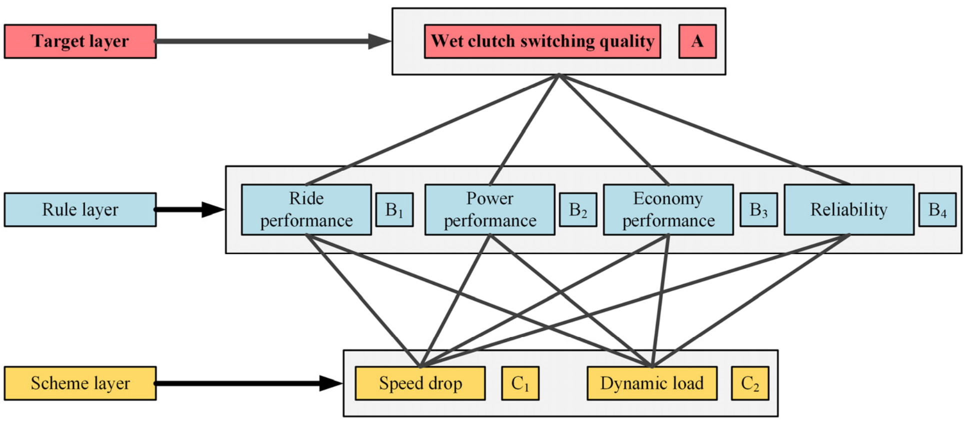


Figure 4. Layers of the wet clutch switching quality.

2.7. Acquisition Method for the Optimal Control Strategy

In this paper, we proposed two methods to obtain the optimal control strategy of the wet clutch adjustable factors (i.e., oil filling pressure and flow rate) with the optimization objective of the minimum comprehensive evaluation index. Consistent results were obtained between the two optimal control strategies.

Method 1: Integrated optimization based on an improved genetic algorithm (I-GA)

Method 1 used an I-GA to optimize the comprehensive evaluation index considering oil pressure and flow as a whole. Heuristic intelligent optimization algorithms are widely used for optimization in the engineering field. A number of studies [37–40] have shown that they can be used to effectively solve engineering problems. The I-GA reference used in this study had been previously studied [41], and its effect in engineering applications had been verified. The flow of this method is shown in Figure 5.

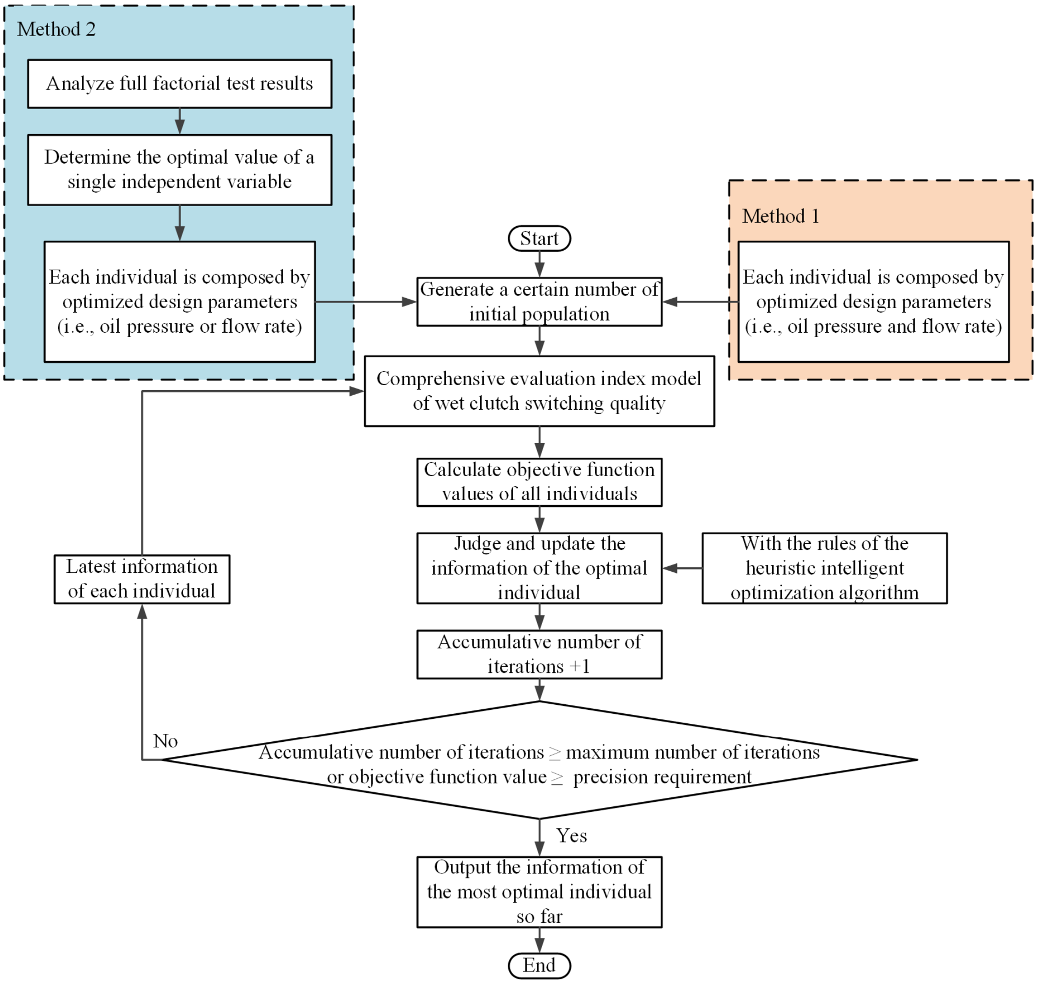


Figure 5. Flow chart of Methods 1 and 2.

Method 2: I-GA-based step-by-step optimization

In each working condition of the agricultural tractor, Method 2 first analyzed the full-factorial test data to obtain the optimal adjustable factor test level combination of dynamic load and speed drop, respectively. The optimal tuning interval for a single independent variable was also determined to hopefully reduce the dimension of the decision variables during the optimization process. Secondly, when the decision variable dimension was reduced, the comprehensive evaluation index model was combined to form a new optimization objective function. Finally, the remaining decision variables were optimized by using the same I-GA from Method 1. The flow of Method 2 is shown in Figure 5.

3. Results and Discussion

3.1. Full-Factorial Simulation Test Results

The full-factorial simulation test results of the working quality of wet clutch switching in an agricultural tractor variable transmission system are shown in Figure 6 for 225 sets of test sample data. The meanings of sample data numbers in Figure 6 are shown in Table 2.

Table 2. The meanings of sample data numbers in Figure 6.

Sample Number	Oil Pressure (MPa)	Flow Rate (L/min)
1~5	2	2~6
6~10	3	2~6
11~15	4	2~6
16~20	5	2~6
21~25	6	2~6

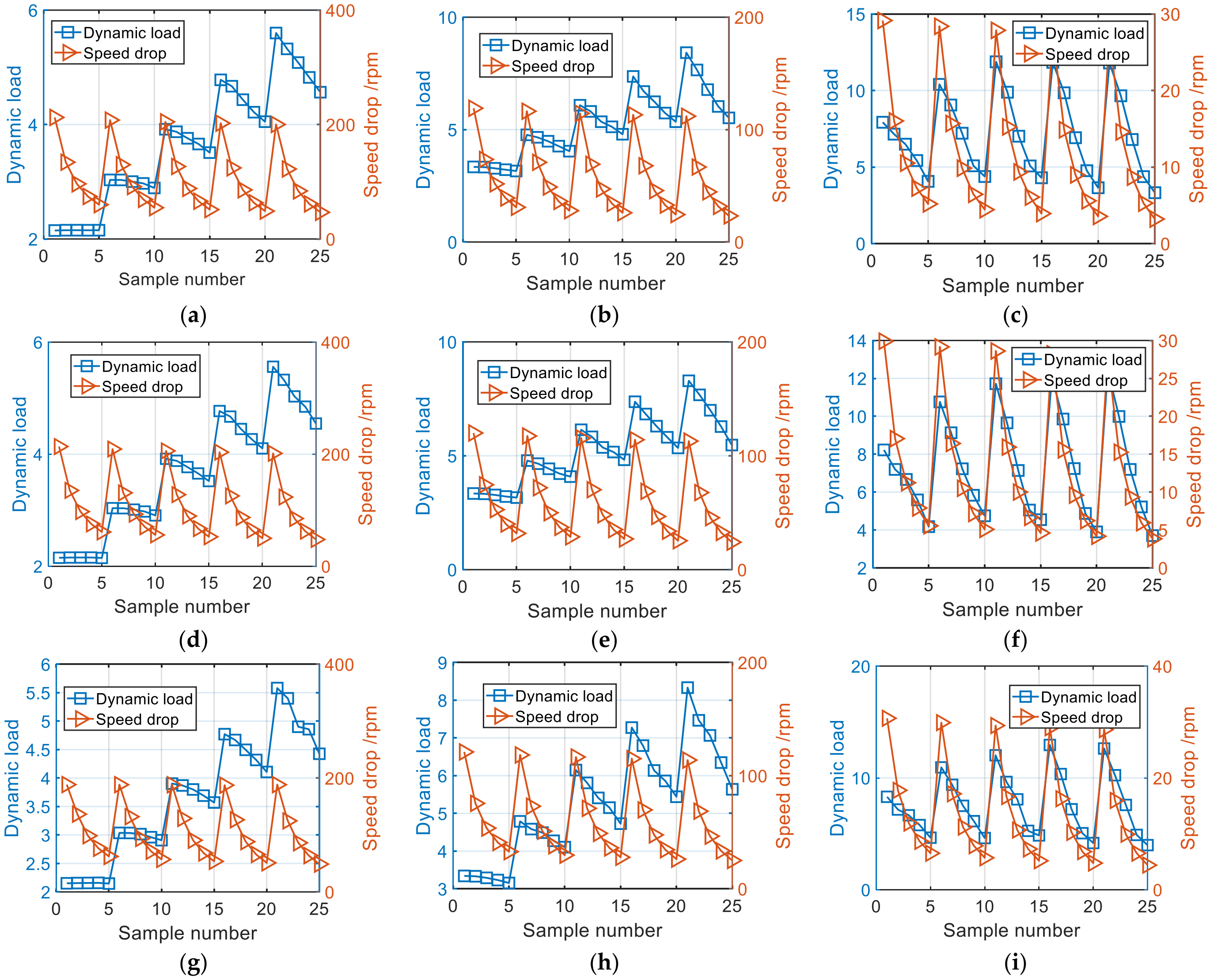


Figure 6. Full-factorial simulation test results: (**a**) High-speed and large-load working condition; (**b**) high-speed and medium-load working condition; (**c**) high-speed and small-load working condition; (**d**) medium-speed and large-load working condition; (**e**) medium-speed and medium-load working condition; (**f**) medium-speed and small-load working condition; (**g**) low-speed and large-load working condition; (**h**) low-speed and medium-load working condition; (**i**) low-speed and low-load working condition.

From Figure 6, there were obvious differences between the dynamic load characteristics and the speed drop characteristics of the agricultural tractor transmission system when the gears were switched. However, the difference between the two tended to decrease with load. In particular, the dynamic load characteristics and the speed drop characteristics were similar under small load conditions. Dynamic load was obviously affected by oil pressure, the flow rate, and the load, and the dynamic load characteristics under the different oil pressures, flow rates, an loads varied significantly. The speed drop was obviously affected by the flow and load, that is, the speed drop characteristics under different flow and load were significantly different.

3.2. Analysis of the Degree of Influence of Working Condition Factors and Adjustable Factors

The results of the influence of working conditions and adjustable factors using PLS are shown in Figure 7.

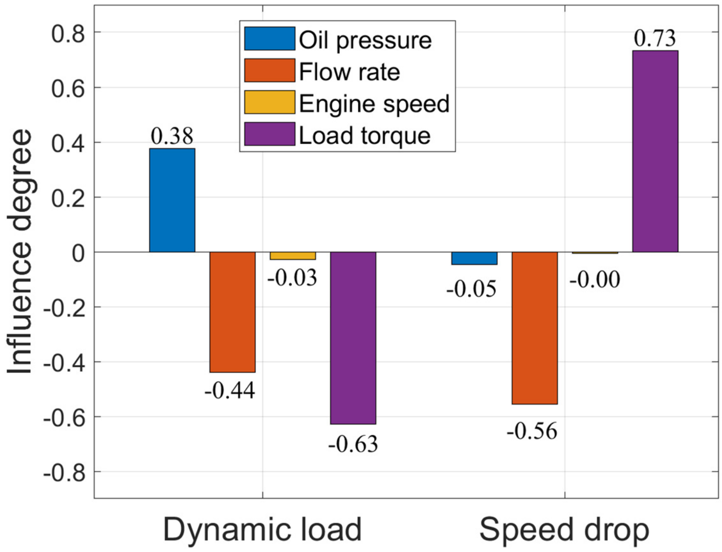


Figure 7. Calculation results based on PLS.

The calculation results based on PLS showed that: (1) The factors with significant influence on dynamic load characteristics were oil pressure, flow rate, and load (from small to large). Among them, oil pressure was positively correlated with dynamic load, and flow rate and load were inversely correlated with dynamic load. (2) The factors that had a significant influence on the speed drop characteristics were flow and load (from small to large). Among them, flow rate was inversely correlated with speed drop, and load was positively correlated with speed drop.

The results of the influence of the RA on working conditions and adjustable factors are shown in Table 3.

Table 3. Calculation results based on the range analysis.

Factor	Oil Pressure	Flow Rate	Engine Speed	Load Torque
Dynamic load range	2.60	2.90	0.17	3.69
Speed drop range (rpm)	6.97	86.44	0.96	94.86

The calculated results of the degree of influence based on the RA were highly consistent with the results of the PLS analysis.

3.3. Establishment and Analysis of a Single Evaluation Index Model

According to the performance evaluation index modeling method proposed in Section 2.5 of this paper, there were three feasible forms to study the available dynamic load characteristic models and speed drop characteristic models. The polynomial models of the three feasible forms are shown below.

Model 1:

$$Q = a_0 + a_1 P + a_2 F \tag{8}$$

where Q is a single evaluation index, namely dynamic load K or speed drop J; a_0~a_2 are the coefficients in Model 1; P is the clutch oil filling pressure; F is the clutch oil filling flow.

Model 2

$$Q = b_0 + b_1P + b_2F + b_3P^2 + b_4PF \tag{9}$$

where b_0~b_4 are the coefficients of each item in Model 2.

Model 3

$$Q = c_0 + c_1P + c_2F + c_3PF + c_4F^2 \tag{10}$$

where c_0~c_4 are the coefficients of each item in Model 3.

The dynamic load characteristic models and speed drop characteristic models of the nine tractor working conditions are shown in Figure 8 (the test group numbers from 1 to 9 are: high-speed and large-load working condition, high-speed and medium-load working condition, high-speed and small-load working condition, medium-speed and large-load working condition, medium-speed and medium-load working condition, medium-speed and small-load working condition, low-speed and large-load working condition, low-speed and medium-load working condition, low-speed and small-load working condition).

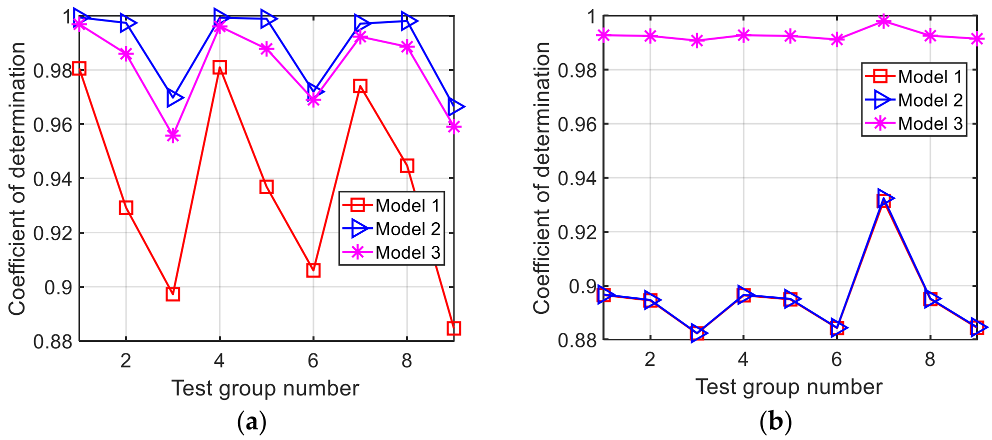


Figure 8. Accuracy comparison of three feasible form models: (**a**) Dynamic load; (**b**) speed drop.

Combined with the forms of the three models and Figure 8, the new forms formed by adding second-order terms and interaction terms (i.e., Model 2 and Model 3) continued to improve the accuracy on the basis of Model 1(specifically, Model 2 improved by 5.5037% and Model 3 improved by 4.7105%). Model 2 had the highest accuracy (the mean coefficient of determination R^2 was 0.9887) and the smallest variance (the variance of nine tractor operating conditions was 0.0002). Therefore, Model 2 had the highest match degree with the dynamic load characteristics.

For speed drop characteristics, Model 1 and Model 2 had similar accuracy (where the mean accuracy of Model 1 was 0.8955 and Model 2 was 0.8958). This suggested that the multivariate first-order linear model had a limited matching degree with the speed drop properties. Moreover, the second-order term of the oil filling pressure had little effect on improving the model accuracy. Model 3 had the highest match with speed drop characteristics (mean accuracy is 0.9927). The first-order term of oil pressure, the first-order term of flow, the second-order term of flow, and the interaction term had the ability to accurately explain the speed drop characteristics. As compared with Model 1 and Model 2, the accuracy of Model 3 was improved by 10.86% and 10.82%, respectively.

Taking the agricultural tractor in high-speed and large-load conditions as an example, the dynamic load characteristic model and speed drop characteristic model are shown in Figure 9.

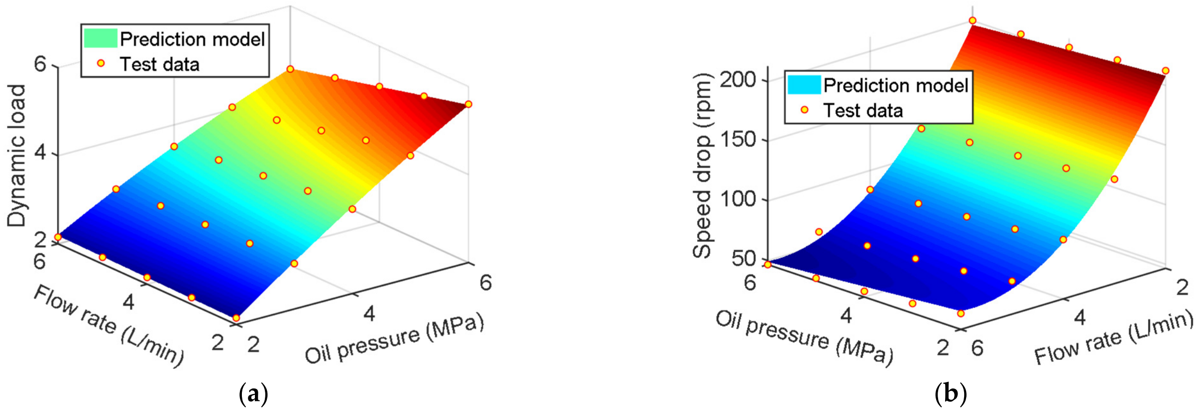


Figure 9. Example of the establishment result of single evaluation index model: (**a**) Dynamic load; (**b**) speed drop.

3.4. Establishment of Comprehensive Evaluation Indicators

The mutual factor weight matrix for each level of wet clutch performance was derived from expert opinion [36]. The mutual factor weights of rule layer B are shown in Table 4, and the mutual factor weights of the scheme layer to the rule layer are shown in Table 5.

Table 4. Mutual factor weights of the rule layer B.

A	B_1	B_2	B_3	B_4
B_1	1	1/2	5	4
B_2	2	1	5	3
B_3	1/5	1/5	1	1/5
B_4	1/4	1/3	5	1

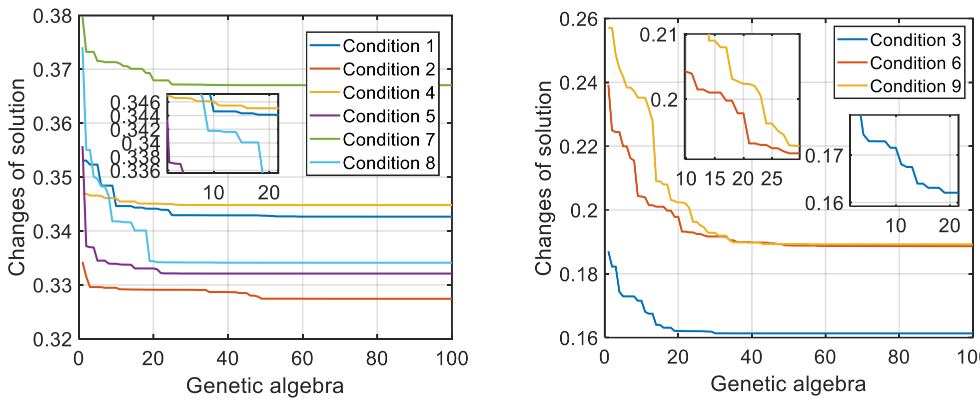
Table 5. Mutual factor weights of scheme layer c for rule layer B.

B	B_1		B_2		B_3		B_4	
	C_1	C_2	C_1	C_2	C_1	C_2	C_1	C_2
C_1	1	1/2	1	2	1	1/3	1	1/2
C_2	2	1	1/2	1	3	1	2	1

In summary, the w_1 and w_2 of the comprehensive evaluation index obtained by the AHP method were 0.4752 and 0.5248, respectively.

3.5. Control Strategy Formulation and Comparison of Adjustable Factors

According to the two control strategy formulation methods proposed in this paper (see Section 2.7), an I-GA was used to optimize the nine working conditions of an agricultural tractor to minimize the comprehensive evaluation index. The iterative evolution curves for Method 1 are shown in Figure 10.



(**a**) (**b**)

Figure 10. Iterative evolution curves of the I-GA (Method 1): (**a**) Medium and high-load working condition; (**b**) small-load working condition.

The control strategies of adjustable factors during wet clutch switching of optimized agricultural tractors are shown in Table 6.

Table 6. Adjustable factor control strategy for wet clutch switching.

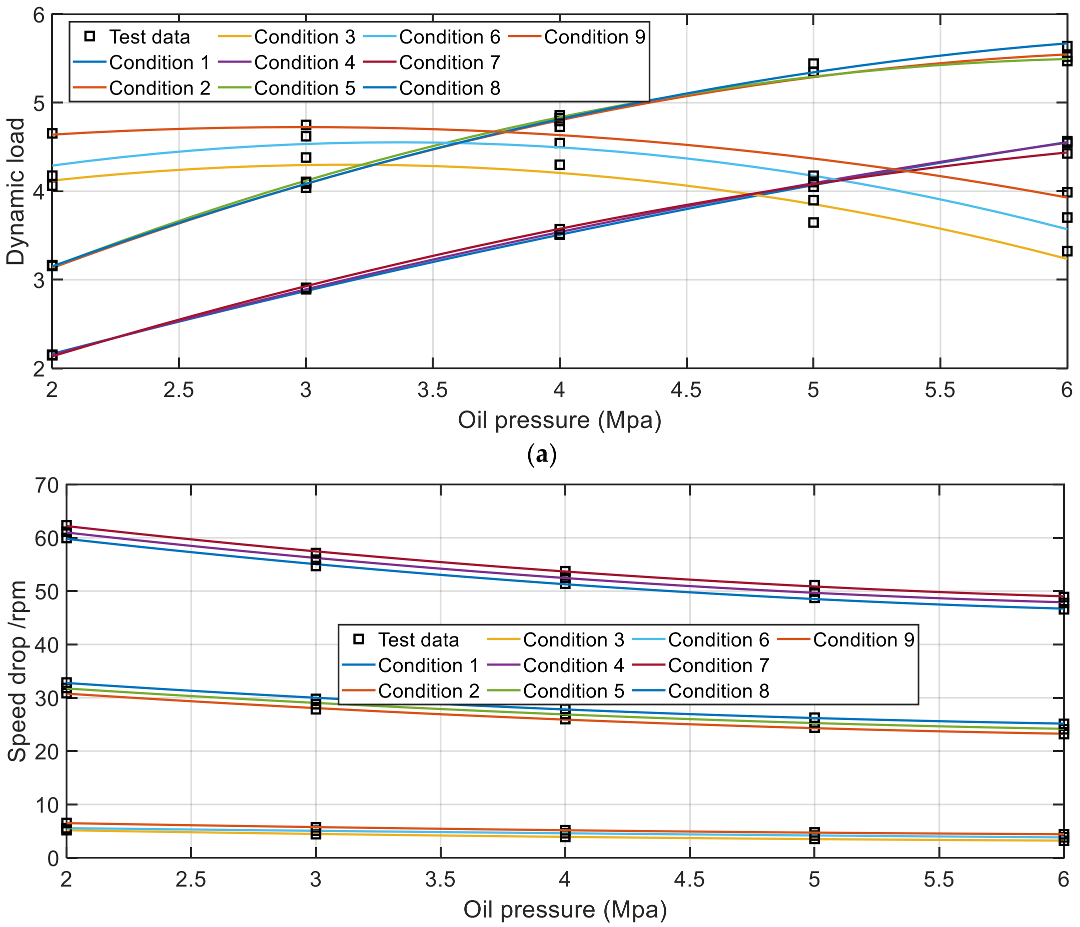
Operating Conditions of Agricultural Tractors	Method 1		Method 2	
	Oil Pressure	Flow Rate	Oil Pressure	Flow Rate
High-speed and large-load	2	5.75	2	6
High-speed and medium-load	2	5.80	2	6
High-speed and small-load	6	6	6	6
Medium-speed and large-load	2	5.76	2	6
Medium-speed and medium-load	2	5.82	2	6
Medium-speed and small-load	6	6	6	6
Low-speed and large-load	2	6	2	6
Low-speed and medium-load	2	5.82	2	6
Low-speed and small-load	6	6	6	6

The full-factorial test data were first analyzed according to Method 2. As compared with the results of 225 sets of test data using the enumeration method, it could be found that the dynamic load and speed drop had relative minimum values when the flow rate was 6 L/min. Therefore, it was determined that the oil filling flow of the wet clutch should be controlled and adjusted to 6 L/min under the full-use condition of am agricultural tractor.

The research combines the whole sample data at the flow level of 6 L/min to obtain the new model after dimension reduction. The new model after dimensionality reduction is shown in Figure 11.

The control strategy was optimized based on the new model after I-GA and dimensionality reduction, and the results are shown in Table 6.

According to Table 6 and the observations of the full-factorial test data, a larger flow rate was beneficial to the speed drop and dynamic load characteristics. The oil pressure regulation strategy was affected by the operating conditions of the agricultural tractor. When the load on the agricultural tractor was small, small oil pressure helped to improve the working quality of the wet clutch. When the load of the agricultural tractor was large, large oil pressure helped to improve the working quality of the wet clutch. The results of the control strategies of Method 1 and Method 2 were highly consistent.



(**a**)

(**b**)

Figure 11. The new model of evaluation index after dimensionality reduction: (**a**) Dynamic load; (**b**) speed drop.

When the dynamic load and speed drop characteristics were improved, the sliding change was further analyzed. Taking the agricultural tractor operation at high-speed and large-load conditions as an example, the maximum sliding value (oil pressure and flow within the respective domain) was 2.49 kJ, and the average value of all test combinations of adjustable factors was 0.63 kJ. Applying the control strategies, the sliding work decreased by 70.19%.

4. Conclusions

Wet clutches are often used in advanced transmission systems for agricultural tractors. Under the action of different factors (mainly including speed, torque, oil pressure, flow, etc.) there are significant differences in wet clutch switching quality. In order to improve the operating characteristics of an agricultural tractor wet clutch, in this paper, we studied the working quality of wet clutch switching under the full-use condition of an agricultural tractor. The effects of four factors (oil pressure, flow rate, engine speed, and load torque) on dynamic load and speed drop are 0.38, −0.44, −0.03, −0.63 and −0.05, −0.56, −0.00, 0.73, respectively. Model 2 should be used for dynamic load characteristics (the mean of R^2 is 0.9887). Model 3 should be used for the speed drop characteristics (the mean of R^2 is 0.9927).

Combined with the two wet clutch adjustable factor control strategies proposed here (based on an I-GA), the agricultural tractor's adjustable factors (oil pressure and flow rate) need not change at high speed, medium speed, or low speed. If an agricultural tractor operates under medium and large loads, oil pressure should be at a smaller value, while flow rate should be at a larger value in their definitional domains, respectively. When an agricultural tractor is under a small-load condition, oil pressure and flow rate should take larger values in each definitional domain. In addition, the research results in this paper show that improving the dynamic load and speed drop can also effectively reduce the sliding friction of a wet clutch.

This study (mainly including the influence of various factors on quality, the establishment of an evaluation index model, and the formulation of control strategies) provides a basis and valuable reference for the design, performance evaluation, performance estimation, as well as control and performance improvement of wet clutches in agricultural machinery.

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