Hindawi
Mathematical Problems in Engineering
Volume 2019, Article ID 2856908, 10 pages
https://doi.org/10.1155/2019/2856908

Research Article

Research on HMCVT Efficiency Model Based on the Improved SA Algorithm

Zhun Cheng, Zhixiong Lu, and Fang Dai

College of Engineering, Nanjing Agricultural University, Nanjing 210031, China

Correspondence should be addressed to Zhixiong Lu; luzx@njau.edu.cn

Received 11 October 2018; Revised 26 December 2018; Accepted 13 January 2019; Published 27 January 2019

Academic Editor: Ramon Sancibrian

Research on the efficiency characteristic of the hydromechanical continuous variable transmission (HMCVT) in tractors is key to obtaining optimal transmission, developing control strategies, and assessing efficiency. To ease and improve the accuracy of obtaining the efficiency completely based on test measurements or theoretical calculation, this study proposes a method for building the HMCVT efficiency model. The method is based on an improved simulated annealing (SA) algorithm according to a small amount of test data. The study uses 8 groups of transmission efficiency values under different operating conditions obtained from bench tests. By theoretical analysis of the HMCVT, this study divides the total transmission efficiency into (i) the transmission efficiency from the output power of the power source to the confluence mechanism, (ii) the transmission efficiency of the confluence mechanism, and (iii) the transmission efficiency of the output part after confluence. The formulas for the three parts of transmission efficiencies are then derived. This study improves the SA algorithm and uses it to identify the three key parameters of hydraulic systems of the transmission efficiency calculation model. Research results indicate that the efficiency model built using the proposed method exhibits high accuracy with an error of about 1.90%. The improved SA algorithm can rapidly complete key parameter identification with an error of about 2.16%; when the displacement ratio is 0, the efficiency values at the same stage are approximately equal under different operating conditions. The HMCVT efficiency model can be built rapidly and effectively with only five groups of efficiency measurement tests.

1. Introduction

Facing complicated working requirements, tractors are necessary to complete heavy-load work, such as tillage and soil preparation and taking delivery of goods, as well as small-medium-load work, such as fertilization and sowing [1–3]. Therefore, tractors require as many operating stages as possible. The hydromechanical continuous variable transmission (HMCVT) can realize free changes in the transmission ratio of tractors while inheriting the high efficiency of the mechanical transmission and high power of the hydraulic transmission [4–6]. As use of tractors increases, research regarding the HMCVT becomes significant [7–10].

Research on the HMCVT efficiency characteristic is key to achieving the optimal transmission ratio of variable speed, developing variable speed control strategies, and assessing the efficiency of the HMCVT design. The HMCVT efficiency characteristic is related to its rotating speed, load, and discharge ratio (or the transmission ratio). To obtain the HMCVT efficiency, numerous tests have to be conducted because of the multiple factors involved [11]. The theoretical calculation of the HMCVT may be a quick process, and the HMCVT efficiency may be easily determined under any operating conditions; however, its accuracy is difficult to ensure.

Studies have rarely been conducted on the total efficiency of the HMCVT. Zhang et al. [12] considered the power cycle and efficiency of the hydraulic unit and developed a formula for determining the HMCVT efficiency; however, the method they proposed was complicated, required experimental research on hydraulic systems, and lacked experimental verification of the total HMCVT efficiency. Guangming Wang et al. [13] established an HMCVT model based on Simulation X, calibrated the model according to experimental data, and then built the efficiency model; however, they calibrated the parameters by repeated manual corrections

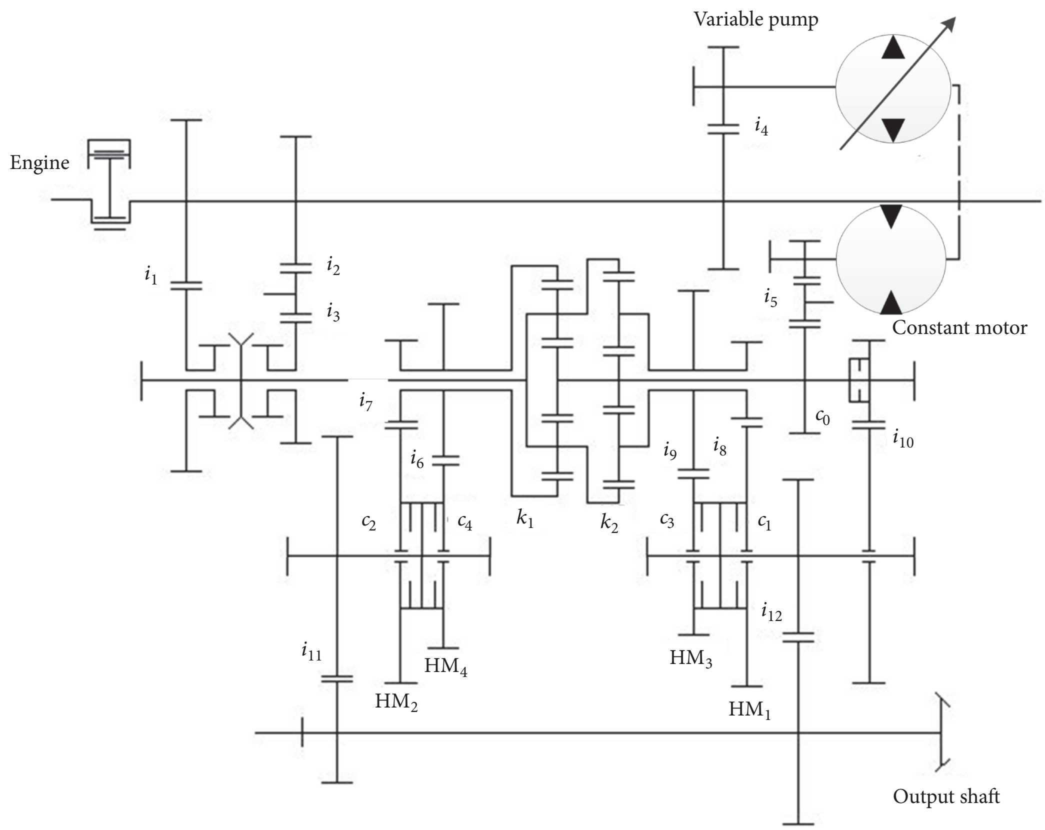

FIGURE 1: Transmission principles of HMCVT in the study.

and required building a model by using Simulation X. Zhang [14, 15] and Xu [16, 17] proposed a method for calculating the HMCVT efficiency by combining the power cycle and efficiency of the hydraulic route; however, the model of the hydraulic route efficiency involved 8 unknown parameters that were difficult to determine, and the calculation process was complex.

To address the aforementioned problems, this study proposes a method for developing the HMCVT efficiency model. The method determines 8 groups of transmission efficiency values under different operating conditions by using bench tests. In accordance with the theoretical analysis of the HMCVT efficiency, the method adopts the improved SA algorithm to identify the key parameters of the calculation model and thereby establish the HMCVT efficiency model. Specifically, the method divides the complex transmission efficiency into three parts: the transmission efficiency from the output power of a power source to the confluence mechanism, the transmission efficiency of the confluence mechanism, and the transmission efficiency of the output part after confluence. The method improves the SA algorithm and uses the algorithm to identify the key parameters of the hydraulic system of the transmission efficiency calculation model. The method proposed in this study for building the transmission efficiency model can determine the HMCVT efficiency under any operating conditions and thus provides a basis for the design and research of the HMCVT as well as the research and development of control strategies.

2. Testing of the HMCVT Efficiency Characteristic

2.1. HMCVT Operating Principles. The HMCVT inputs the power output from the power source into the pump-motor hydraulic transmission system and the gear-engagement mechanical transmission system. After coupling of the hydraulic part and the mechanical part of the transmission power via the confluence mechanism, the HMCVT outputs the power [18, 19]. The hydraulic system can realize the continuous variation of the speed ratio in accordance with the changes in the displacement ratio, prompting the HMCVT to realize the continuous variation of the transmission ratio within a certain range. The HMCVT under study has 1 pure hydraulic stage H_0, 4 hydromechanical continuous variable speed stages HM_1–HM_4, 12 gear pairs, and 5 wet clutches c_0–c_4. Figure 1 illustrates the transmission principles of the HMCVT.

Table 1 lists the HMCVT parameters.

2.2. Measurement Uncertainty of Transmission Efficiency. To meet the required maximum engine speed of < 2400 r/min (Weichai WP6T180E21), we use a JC3A rotational speed and torque sensor (XiangYi Dynamic Test Instruments Co., Ltd.)

Table 1: HMCVT parameters.

i_1	i_2	i_3	i_4	i_5	i_6	i_7
1.439	0.969	1.484	0.678	1.96	0.982	3.52
i_8	i_9	i_{10}	i_{11}	i_{12}	k_1	k_2
2.767	0.794	2.767	0.823	1.093	2.56	3.56

Note: i_1–i_{12} are the transmission ratios of the 12 gear pairs; k_1 and k_2 are the characteristic parameters of the planetary rows.

as the test bench, with a rotational speed of 0–3000 r/min and a torque range of 0–5000 N · m. In accordance with the operations manual provided by the manufacturer, the sensor errors in torque and rotational speed measurement are not greater than 10 N · m and 1 r/min, respectively.

Our analysis indicates that the measurement error of the HMCVT transmission efficiency is determined using the JC3A rotational speed and torque sensor. The measurement uncertainty is the uncertainty of measurement results caused by random changes in factors, such as the experimental conditions during repeated measurement and the accuracy of the measuring instrument [20]. The current study evaluates the measurement uncertainty of the HMCVT efficiency by using two methods: statistical analysis of the observation columns (uncertainty evaluation caused by random effect) and empirical evaluation based on the assumed probability distribution of other information (the uncertainty evaluation caused by the system).

We measure the torque and the rotational speed with the JC3A rotational speed and torque sensor repeatedly (10 times) under similar operating conditions. On the basis of the measurements, we obtain the following data after calculation: the mean of torque measurements is 100.4720 N · m, and the standard deviation is 0.8889 N · m. The mean of rotational speed measurements is 78.6820 rad/s, and the standard deviation is 0.5309 rad/s. The formula for uncertainty evaluation caused by a random effect is as follows [21]:

$$U_1 = \frac{s(u)}{\overline{u}} = \frac{\sqrt{(1/(n-1))\sum_1^n (u_i - \overline{u})^2}}{\overline{u}} \tag{1}$$

where U_1 is the measurement uncertainly caused by a random effect, $\overline{u}$ is the mean of the measurements, $s(u)$ is the standard deviation of measurements, n is the number of measurements, and u_i is the value of the i^{th} measurement.

We determine by calculation that the measurement uncertainties caused by the random effect of torque and rotational speed are 0.88% and 0.67%, respectively.

The following is the calculation formula for the uncertainty evaluation attributed to a system effect:

$$U_2 = \frac{\max \Delta u}{K} \tag{2}$$

where U_2 is the uncertainty caused by the system effect, $\max \Delta u$ is the maximum measurement effort of the instrument, and K is related to the probability statistical distribution law of error with a value of $\sqrt{3}$ because of the uniform distribution satisfied by the instrument used in the study.

We know by calculation that the measurement uncertainties caused by the system effect of the torque and rotational speed are 0.12% and 0.019%, respectively.

The four aforementioned uncertainties are independent and uncorrelated; thus, the total uncertainty of the HMCVT efficiency measurement is

$$U = \sqrt{uu_1^2 + uu_2^2 + uu_3^2 + uu_4^2} \tag{3}$$

where U is the total uncertainty of the transmission efficiency measurement; uu_1, uu_2, uu_3, and uu_4 are the measurement uncertainties caused by the random effect of torque and rotational speed and the measurement uncertainties caused by the system effect of torque and rotational speed.

Finally, using formula (3), we determine that the total uncertainty of the HMCVT efficiency is 1.12%. The HMCVT efficiency obtained in this study exhibits high accuracy with minimal errors. The errors resulting from the subsequent parameter identification are also small.

2.3. Transmission Efficiency Measurement Testing. We can obtain the total transmission efficiency of the whole system by measuring the rotational speed and torque of the engine output end as well as the rotational speed and torque of the transmission output end by using the bench test. Figure 2 shows the test bench of the HMCVT.

We choose stage HM_4 for the test. Limited by the test cost and conditions of the test site and considering that this study proposes the method to build a high-accuracy calculation model for the HMCVT efficiency with a small amount of test data, this study only measures 8 groups of HMCVT efficiencies under different operating conditions and ensures the accuracy of each group of test data. Table 2 lists the results of the transmission efficiency tests.

3. New Calculation Model for HMCVT Efficiency

Considering that the bench test uses the HMCVT stage HM_4, we only conduct a theoretical analysis of the stage and build a transmission efficiency calculation model of the stage. The calculation models of other stages or other HMCVTs can be obtained in a similar way.

With regard to the HMCVT used in the study, the power of stage HM_4 after being output from the engine in one route is transmitted to the variable-pump-constant-displacement-motor system and then output into the confluence mechanism via the sun gear of the planetary row k_1; in the other route, the power of stage HM_4 is transmitted completely by the gear to the planetary carrier of the planetary row k_1. This

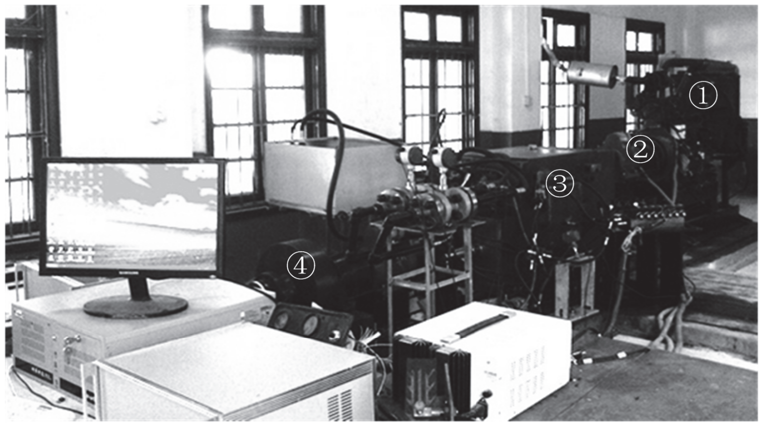

Figure 2: HMCVT test bench. Note: ① engine (Weichai WP6T180E21); ② JC3A rotational speed and torque sensor; ③ HMCVT; ④ dynamometer.

Table 2: HMCVT efficiency testing results.

Test No.	Displacement Ratio	Angular Velocity of the Output Shaft of the Engine (rad/s)	Load Torque ($N \cdot m$)	Transmission Efficiency (%)
1	-1	78.54	101.86	64.3
2	-0.73	78.54	127.32	69.8
3	0.73	78.54	267.38	80.8
4	1	78.54	292.85	76.6
5	-1	146.61	163.70	58.8
6	0	78.54	190.99	84.7
7	0	102.10	235.06	81.2
8	0	126.19	340.76	84.4

study omits the transmission loss in the clutch. The following is the calculation formula for solving the rotational speed of the planetary carrier, gear ring, and sun gear of the confluence mechanism [22–24]:

$$k_1 n_r = (1 + k_1)\, n_c - n_s \tag{4}$$

where n_r is the output rotational speed of the gear ring, n_c is the input rotational speed of the planetary carrier, and n_s is the input rotational speed of the sun gear.

The transmission ratio i_{HM} of Stage HM_4 is expressed as

$$i_{HM} = \frac{(1 + k_1)\, i_4 i_5 + \varepsilon i_2 i_3}{k_1 i_2 i_3 i_4 i_5 i_6 i_{11}} \tag{5}$$

According to [11], the formula for determining Δp, the pressure difference between the inlet and outlet oil circuits of the constant displacement motor, is

$$\Delta p = \frac{2\pi T_m}{D_m} + \frac{2\pi T_f}{D_m} = \frac{2\pi T_{out}}{i_5 i_6 i_{11} k_1 D_m} - \frac{2\pi^2 f_m \varepsilon n_e}{30 D_m i_4} \tag{6}$$

where Δp (Mpa) is the pressure difference between the inlet and outlet oil circuits of the constant displacement motor; T_m ($N \cdot m$) is the torque of the motor output end; T_f ($N \cdot m$) is the viscous resistance torque of the motor output shaft; D_m (cm^3/r) is the specified discharge of the motor; T_{out} ($N \cdot m$) is the torque of the HMCVT output end; f_m is the viscous damping coefficient; and n_e (r/min) is the engine speed.

The HMCVT has a complex structure. Accordingly, we divide the HMCVT efficiency into three tandem parts in accordance with the transmission method of the engine output power for convenience in calculating the transmission efficiency.

Part 1 is η_{M1}, the transmission efficiency from the output power of the engine to the confluence mechanism. For convenience in calculation, the transmission loss in the hydraulic route is not considered in calculating Part 1; however, it is taken into consideration in Part 2. Therefore, η_{M1} is determined using the following:

$$\eta_{M1} = (1 - a_1)\, \eta_2 \eta_3 + a_1 \tag{7}$$

where a_1 is the percentage of the hydraulic route input power in the total output power of the engine and η_2 and η_3 are the transmission efficiencies of the corresponding gear pairs.

The HMCVT in the study is of the output split type. Thus, e_H, the split ratio of the hydraulic power of the confluence mechanism, is the ratio of the input power transmitted to the planetary row via the hydraulic route to the output power of the gear ring. The HMCVT is determined using the following:

$$e_H = 1 - \frac{i_{HM}}{(1+A)} \tag{8}$$

where A is the connecting characteristic parameter given by $A = -1/(1+k_1)$. According to the definition of the hydraulic power split ratio e_H,

$$e_H = \frac{a_1 P_I \eta_4 \eta_H \eta_5}{P_r} \tag{9}$$

where P_I (W) is the total output power of the engine; η_4 and η_5 are the transmission efficiencies of the corresponding gear pairs; η_H is the transmission efficiency of the pump-motor system; and P_r (W) is the output power of the gear ring.

By analysis of the input power of the planetary carrier of the confluence mechanism,

$$(1-a_1) P_I (\eta_3 \eta_2) = \frac{P_r}{\eta_{HM}} - a_1 P_I \eta_4 \eta_H \eta_5 \tag{10}$$

where η_{HM} is the transmission efficiency of the confluence mechanism.

In accordance with formulas (8), (9), and (10), a_1 is derived using the following:

$$a_1 = \frac{e_H}{\left[\left(\left(1/\eta_{HM} - e_H\right)/\eta_3\eta_2\right)\eta_4\eta_H\eta_5 + e_H\right]} \tag{11}$$

Part 2 is the transmission efficiency η_{HM} of the confluence mechanism. The loss caused by the circulation power is the major consideration in this part of the efficiency. According to the analysis, a hydraulic power split ratio $e_H < 0$ indicates a hydraulic circulation power, whereas $0 \leq e_H \leq 1$ indicates that the system is in a hydraulic–mechanical split-transmission state and thus has no circulation power. η_{HM} is given by

$$\eta_{HM} = \begin{cases} \dfrac{(1+A)/i_{HM}}{\eta'_H (1+A)/i_{HM} - \eta'_H + 1} & e_H < 0 \\ \dfrac{\eta'_H (1+A)/i_{HM}}{(1+A)/i_{HM} + \eta'_H - 1} & 0 \leq e_H \leq 1 \end{cases} \tag{12}$$

where η'_H is the tandem transmission efficiency of the pump-motor system, gear pair 4, and gear pair 5, and $\eta'_H = \eta_H \eta_4 \eta_5$.

The loss of the hydraulic route in Part 1 mainly consists of the transmission losses of gear pair 4 and gear pair 5. For convenience in calculation, we cascade the pump-motor system, gear pair 4, and gear pair 5 into an integral whole and integrate the transmission loss into the calculation model of Part 2.

As shown in formula (12), an important influencing factor of the confluence mechanism transmission efficiency η_{HM} is the transmission efficiency η_H of the pump-motor system. To build a reliable pump-motor hydraulic system model, we use the following formulas [25]:

$$V_p \omega_p \varepsilon = V_m \omega_m + \frac{C_s \Delta p \left(V_p + V_m\right)}{\mu} + \frac{V_0 d\Delta p}{\beta_e dt} \tag{13}$$

$$\Delta p V_m = \frac{J_m d\omega_m}{dt} + f_m \omega_m + T_m + c_{fm} \Delta p V_m \tag{14}$$

$$\Delta p V_p \varepsilon = -\frac{J_p d\omega_p}{dt} - f_p \omega_p + T_p + c_{fp} \Delta p V_p \varepsilon \tag{15}$$

where V_p and V_m (m^3/rad) are the specified discharges of the variable pump and the constant discharge motor, respectively; ω_p and ω_m (rad/s) are the angular velocities of the variable pump and the constant discharge motor, respectively; T_p and T_m ($N \cdot m$) are the shaft torques of the variable pump and the constant discharge motor; C_s is the total leakage coefficient; μ (m^3) is the dynamic viscosity of the hydraulic oil; V_0 is the working volume of the hydraulic oil; β_e (Pa) is the bulk modulus of the elasticity of the hydraulic oil; J_m and J_p ($kg \cdot m^2$) are the shaft rotational inertias of the variable pump and the constant displacement motor; J_m is 0.0049 and J_p is 0.0054; f_m and f_p ($N \cdot m \cdot s$/rad) are the viscous damping coefficients of the variable pump and the constant displacement motor; c_{fm} and c_{fp} are the mechanical friction loss coefficients of the variable pump and the constant displacement motor, which exert insignificant effects and have values equal to 0.01 in this study.

The HMCVT efficiency in this study is not the transmission efficiency at some instant stages but one of the entire system becoming stable under certain operating conditions. Thus, the quantities in formulas (13), (14), and (15) for time differentiation can be disregarded. In this case, the parameters to be identified in the variable-pump-constant-discharge-motor system are $C_s(V_p + V_m)/\mu$, f_m, and f_p.

Formulas (13), (14), and (15) can be used to derive the rotational speed ω_p and rotational torque c of the variable pump, as well as rotational speed ω_m and rotational torque T_m of the constant displacement motor. The formula for the transmission efficiency η_H of the pump-motor system is given by

$$\eta_H = \frac{\omega_m T_m}{\omega_p T_p} \tag{16}$$

Part 3 is η_{M2}, the transmission efficiency output from the confluence mechanism to the output part of the HMCVT. The transmission loss in this part is completely the transmission loss of the gear engagement. The formula for η_{M2} is as follows:

$$\eta_{M2} = \eta_6 \eta_{11} \tag{17}$$

where η_6 and η_{11} are the transmission efficiencies of the corresponding gear pairs.

In accordance with the aforementioned formulas, the calculation model of the HMCVT total transmission efficiency η_{total} is as follows:

$$\eta_{\text{total}} = \eta_{M1} \eta_{HM} \eta_{M2} \tag{18}$$

The calculation model includes the three parameters to be identified: $C_s(V_p + V_m)/\mu$, f_m, and f_p. The parameters should be identified according to the specific test data to ensure the accuracy of the transmission efficiency calculation model.

4. Parameter Identification Based on Improved SA Algorithm and Result Analysis

4.1. Enhancements in SA Algorithm. The SA algorithm is a heuristic intelligent optimization algorithm with fast convergence [26–28]. The concept of SA was developed from the principle of solid annealing. The following are the general steps of the SA algorithm. First, the following are optimized: initial temperature t_0, a_t, the temperature reduction coefficient in each iteration, the final temperature t_{end} and $x_0 = (x_{01}, x_{02}, x_{03}..., x_{0n})$, and the initial value of the parameter to be optimized. The objective function needed for algorithm iteration is then determined, and the initial value of the parameter to be optimized is substituted to obtain the initially optimal objective function value. The initial parameter x_0 is assigned a certain disturbance value to obtain the new parameter value $x_1 = (x_{11}, x_{12}, x_{13}..., x_{1n})$, which is then substituted in the calculation to obtain the new objective function value. $\Delta E(x_1)$, the difference between the objective function value obtained from the calculation and the optimal objective function value in the previous generation, is determined. If $\Delta E(x_1) \le 0$, x_1 is accepted; if $\Delta E(x_1) > 0$, x_1 is accepted with a probability of $P = \exp(-\Delta E/t)$, where t is the current temperature. The aforementioned process is repeated continuously until the temperature is reduced to the final temperature t_{end}. The algorithm ends the iteration and outputs the optimal parameter value and the optimal objective function value.

The system with parameters to be identified in this study is complex. To improve the rate and accuracy of convergence of the SA algorithm and prevent prematurity, this study improves the SA algorithm as follows.

(1) Change the end conditions of the algorithm and set a threshold value γ. If the objective function value is smaller than the threshold value γ in a generation, the algorithm ends the iteration.

(2) Improve the disturbing function of the SA algorithm by using the non-uniform mutation of the genetic algorithm for reference, aimed at providing the algorithm iteration a large search space in the initial stages and a strong local search ability in the later stages. The new disturbing function is as follows:

$$x_{i+1} = x_i + L_x (rand - 0.5) \left(1 - \frac{i}{N+2}\right) \tag{19}$$

where x_i is the value of the parameter of the i^{th} generation to be optimized; L_x is 0.1 times the definitional domain of the parameter to be optimized; N is the theoretical maximum number of iterations at temperatures from t_0 to t_{end}.

(3) To enhance the search ability of the algorithm in the evolutionary process, the temperature reduction coefficient a_t is expected to be the maximum value at the stage where the optimal objective function value changes; the temperature reduction coefficient a_t is the minimum value at the stage where the optimal objective function value remains unchanged. The value of a_t is set as follows:

$$a_t = \begin{cases} 0.9 & \Delta E(x_i) < 0 \\ 0.7 & \Delta E(x_i) \ge 0 \end{cases} \tag{20}$$

where $\Delta E(x_i)$ is the difference between the objective function value of the i^{th} generation and the optimal objective function value of the previous generation.

(4) To improve the parameter identification efficiency and reduce the complexity of the calculation, a new parameter to be identified was introduced by piecewise parameter identification using Magic Formula for [29]. The transmission efficiency η_H of the pump-motor system was introduced to the three aforementioned parameters, increasing the total number of parameters that have to be identified to four. Parameter identification is then divided into two parts: Part 1 to identify the parameter η_H and Part 2 to the identify parameters $C_s(V_p + V_m)/\mu$, f_m, and f_p.

4.2. Parameter Identification Results and Analysis. This study uses the improved SA algorithm for the two-part parameter identification. In Table 2, the data of tests 1, 2, 4, 5, and 6 are used as substitution data in the objective function of optimization algorithm for parameter identification; the data of tests 3, 7, and 8 are used as the data to verify parameter identification results.

The test measurements of 6, 7, and 8 in Table 2 show that when the displacement ratio $\varepsilon = 0$, the HMCVT total transmission efficiencies at the same stage are almost equal under different operating conditions. When the displacement ratio $\varepsilon = 0$, the constant displacement motor does not apply work externally; thus, the theoretical transmission efficiency of the pump-motor system is $\eta_H = 0$. However, in the numerical calculation model, 0 is a special value causing the failure of many formulas under normal operating conditions. If the displacement ratio $\varepsilon = 0$, the HMCVT transmission efficiency is also 0 in accordance with formula (12). This result is not consistent with the actual result because although the hydraulic part does not apply work externally, the mechanical part transmits power all the time. In engineering, it is generally considered as $10^{-4} \approx 0$; thus, this study proposes that when the displacement ratio $\varepsilon = 0$, then the value of η_H is any nonzero positive in the range of $\eta_H < 10^{-4}$. Using formula (12), we know that the transmission efficiency $\eta_{HM} \approx 0.8605$ of the confluence mechanism tallies with the actual test data.

The actual transmission efficiency of the gear is about 0.96–0.99. To evaluate the effect of gear efficiency on the HMCVT transmission efficiency model, this study chooses gear transmission efficiency $\eta_{gear} = 1$, 0.99, 0.98, 0.97, and 0.96, by using the enumeration method for the parameter identification test. We adopt the improved SA and use RSQ (coefficient of determination) as the objective function for the iteration of the algorithm. The closer the value of RSQ to 1, the higher the parameter identification accuracy. The formula for RSQ is given by

$$RSQ = 1 - \frac{\sum_{i=1}^{n} \left[F_{x\_predicted}(x_i) - F_{x\_measured}(x_i)\right]^2}{\sum_{i=1}^{n} \left[F_{x\_predicted}(x_i) - \left(\sum_{i=1}^{n} F_{x\_measured}(x_i)\right)/n\right]^2} \tag{21}$$

where $F_{x\_predicted}$ is the predicted value of the HMCVT transmission efficiency; $F_{x\_measured}$ is the measured value of the HMCVT transmission efficiency; x_i represents the i^{th} group of the experimental measurements (displacement ratio, angular velocity of the engine output shaft, and load torque); and n is the total number of measured values.

Table 3: Tests of gear transmission efficiency effect.

Gear Transmission Efficiency	Average Error of All Data (%)	Average Error of Parameter Identification (%)	Average Error of Prediction (%)
1	5.35	2.07	10.83
0.99	5.41	1.63	11.72
0.98	2.06	2.16	1.90
0.97	2.37	2.69	1.83
0.96	3.31	3.25	3.39

Table 4: Comparison of estimated values and actual values of HMCVT transmission efficiency.

Test No.	Estimated Value of Transmission Efficiency (η_{gear} = 0.98) (%)	Estimated Value of Transmission Efficiency (η_{gear} = 0.97) (%)	Measured Value of Transmission Efficiency Test (%)
1	64.30	64.30	64.3
2	69.23	68.73	69.8
3	82.33	81.32	80.8
4	76.60	76.60	76.6
5	63.52	63.43	58.8
6	82.55	80.77	84.7
7	82.56	80.79	81.2
8	82.54	80.73	84.4

Table 3 lists the HMCVT transmission efficiency results after parameter identification given different gear transmission efficiencies.

Column 2 of Table 3 shows the average error of the transmission efficiencies, obtained after parameter identification with a certain gear transmission efficiency and all test measurement values (8 groups in total). Column 3 shows the average error for the transmission efficiencies obtained after parameter identification, given a certain gear transmission efficiency and the test measurement values involved in parameter identification (tests 1, 2, 4, 5, and 6). Column 4 shows the average error of the transmission efficiency values obtained after parameter identification and the test measurement values not involved in parameter identification (tests 3, 7, and 8).

Given the relatively small error of gear transmission [30, 31], researchers generally consider the loss of gear transmission negligible and consider the gear transmission efficiency to be approximately equal to 1. Parameter identification results indicate that the transmission efficiency of the gear pair largely influences the accuracy of the transmission efficiency model. Table 3 shows that the gear transmission efficiency η_{gear} in the HMCVT efficiency calculation model should be 0.98 or 0.97.

When the gear transmission efficiency η_{gear} is 0.98, the identification results for $C_s(V_p + V_m)/\mu$, f_m, and f_p are 4.67×10^{-12}, 0.0333, and 0.5613, respectively; when the gear transmission efficiency η_{gear} is 0.97, the identification results for $C_s(V_p + V_m)/\mu$, f_m, and f_p are 2.43×10^{-12}, 0.0311, and 0.2934, respectively. Table 4 presents a comparison of the estimated values and actual values of the HMCVT transmission efficiency.

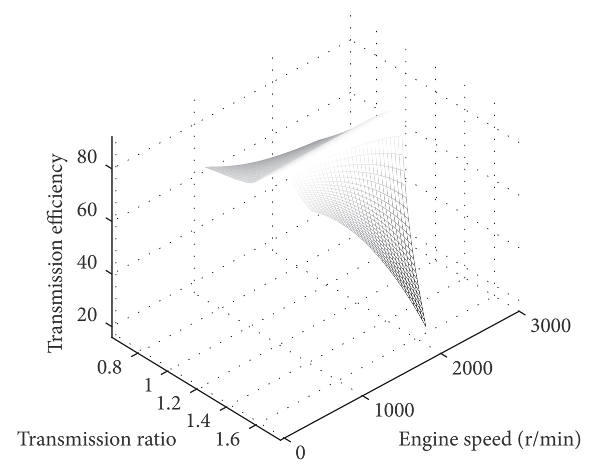

Figure 3: HMCVT transmission efficiency with 40 kW load power.

Table 4 shows that when the gear transmission efficiency η_{gear} = 0.98, the estimated value is closer to the actual value (the average value is about 83.4%); when the displacement ratio $\varepsilon = 0$, this value is used as the calculation parameter of the HMCVT transmission efficiency model. We choose the load power of 40, 60, and 80 kW and then determine the HMCVT total transmission efficiency. The engine speed changes from the minimum stable speed of 750 r/min to the specified speed of 2200 r/min, and the range of the HMCVT transmission ratio when the displacement ratio changes from -1 to +1 under the three operating conditions, as shown in Figures 3–5.

To verify the effect and computational complexity of the improved SA algorithm for parameter identification

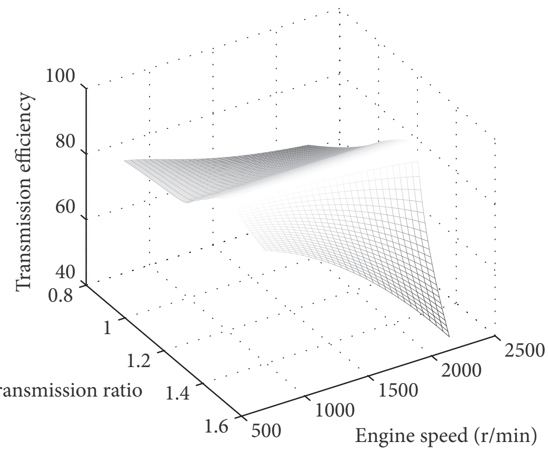

Figure 4: HMCVT transmission efficiency with 60 kW load power.

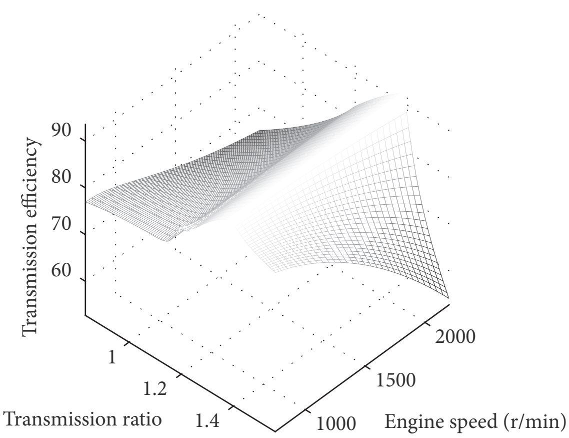

Figure 5: HMCVT transmission efficiency with 80 kW load power.

of the HMCVT transmission efficiency, this study chooses the standard genetic algorithm (GA) and standard particle swarm optimization (PSO) for comparison testing. Both algorithms are heuristic intelligent optimization algorithms that are commonly used in scientific research [32–34]. The test for parameter identification effect chooses the gear transmission efficiency of 0.98. A Lenovo computer with Intel(R) Core(TM) i5-4590 processor @3.30 GHz and 8 GB memory is used in the current study. Both standard PSO and standard GA adopt 20 particles, and the number of iterations is set as 50. Figure 6 shows the test results.

Figure 6 shows that the standard PSO and the standard GA are within the area of local optimum. The globally optimal value is slowly determined as the number of iteration increases. Meanwhile, the improved SA quickly locates the area of the global optimum and finally converges to the global optimal value. Specifically, the improved SA spends 0.21 s on 12 iterations, with a transmission efficiency error of 0.00039; the standard GA spends 0.47 s on 50 iterations, with a transmission efficiency error of 0.0039; the standard PSO spends 0.36 s on 50 iterations with a transmission efficiency error of 0.0042. Therefore, the improved SA used in the study

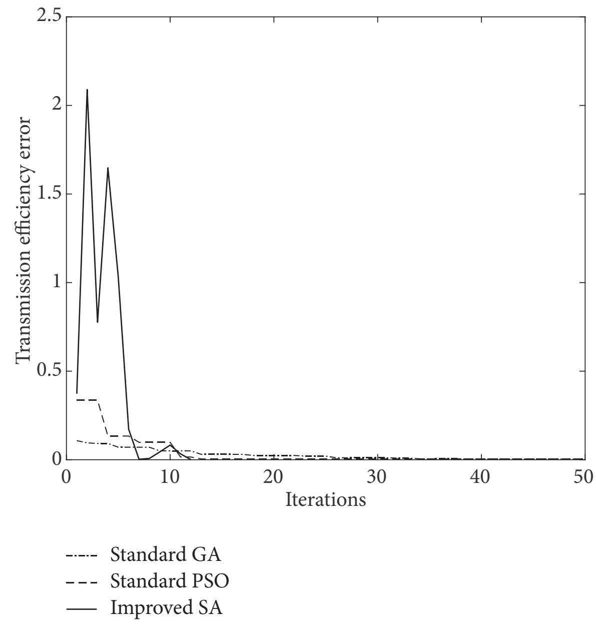

Figure 6: Iteration evolution curves of parameter identifications of three algorithms.

exhibits high convergence accuracy and uses less time for parameter identification.

5. Conclusions

(1) This study proposes a method for building the HMCVT efficiency model. Research results show that the method only requires 5 groups for measurement testing of the HMCVT transmission efficiency under different operating conditions in order to build a model for calculating the HMCVT transmission efficiency quickly and effectively by parameter identification. The estimation error of the transmission efficiency is about 1.90%.

(2) The SA algorithm enhancements contributed by this study lead to desirable results. The two-part parameter identification reduces the complexity of the calculation. The algorithm exhibits no prematurity during parameter identification and can effectively converge to the global optimal solution of the parameter to be identified. The average error of the parameter identification results is about 2.16%.

(3) At displacement ratio $\varepsilon = 0$, the transmission efficiency of the pump-motor system should be any nonzero positive $< 10^{-4}$. The calculation results of the proposed HMCVT transmission efficiency model and the measurement results of the bench test indicate that, at displacement ratio $\varepsilon = 0$, the total transmission efficiencies of the HMCVT at the same stage are approximately equal under different operating conditions.

(4) The gear transmission loss is small, but the gear transmission efficiency η_{gear} significantly affects the accuracy of the HMCVT transmission efficiency model when it ranges from 0.96 to 1. The results show that the optimal gear transmission efficiency is 0.98.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

This paper is supported by the National Key Research and Development Plan (2016YFD0701103) and Postgraduate Research & Practice Innovation Program of Jiangsu Province (KYCX17_0647).

References

[1] M. Liu, Z. Zhou, L. Xu, J. Zhao, and X. Yan, "Multi-objective optimization and design of tractor trailer systems," *Transactions of the Chinese Society of Agricultural Engineering*, vol. 33, no. 8, pp. 62–68, 2017.

[2] S. Fang, Z. Lu, Z. Wang et al., "Design and prototype performance experiments of steering-by-wire hydraulic pressure system of tractor," *Transactions of the Chinese Society of Agricultural Engineering*, vol. 33, no. 10, pp. 86–93, 2017.

[3] S. Raikwar, V. K. Tewari, S. Mukhopadhyay, C. R. Verma, and M. Sreenivasulu Rao, "Simulation of components of a power shuttle transmission system for an agricultural tractor," *Computers and Electronics in Agriculture*, vol. 114, pp. 114–124, 2015.

[4] Z. Zhu, X. Gao, L. Cao, Y. Cai, and D. Pan, "Research on the shift strategy of HMCVT based on the physical parameters and shift time," *Applied Mathematical Modelling*, vol. 40, no. 15-16, pp. 6889–6907, 2016.

[5] Z. Zhu, X. Gao, D. Pan, Y. Zhu, and L. Cao, "Study on the control strategy of shifting time involving multigroup clutches," *Mathematical Problems in Engineering*, vol. 2016, Article ID 9523251, 17 pages, 2016.

[6] M. Zhang and Z. Zhou, "Modeling and control simulation for the multi-range hydro-mechanical CVT," *Key Engineering Materials*, vol. 621, pp. 462–469, 2014.

[7] G. W. Cheng, Z. L. Zhou, Q. Y. Men, and C. N. Deng, "The Study on the measurement and testing technology of the HMCVT hydraulic pressure based on the data fusion technology," *Journal of Physics: Conference Series*, vol. 48, no. 1, pp. 1289–1294, 2006.

[8] L. Xu, Z. Zhou, M. Zhang, and Y. Li, "Speed ratio matching strategies of hydro-mechanical continuously variable transmission system of tractor," *Journal of China Agricultural University*, vol. 11, no. 4, pp. 94–98, 2006.

[9] L. Xu, Z. Zhou, M. Zhang, and Y. Li, "Reasonable matching of engine and hydro-mechanical continuously variable transmission system of tractor," *Transactions of the Chinese Society of Agricultural Engineering*, vol. 22, no. 9, pp. 109–113, 2006.

[10] X. Gao, Z. Zhu, and Y. Zhu, "Analysis of transmission characteristics of HMCVT," *Journal of ChongQing JiaoTong University*, vol. 32, no. 4, pp. 715-716, 2013.

[11] G. Wang, *Study on Characteristics, Control and Fault Diagnosis of Tractor Hydro-Mechanical CVT*, Nanjing Agricultural University, Nanjing, China, 2014.

[12] H. Li, M. Zhang, X. Chen, and Z. Zhou, "Efficiency Analysis of an Innovational Multi-range Hydro-mechanical Continuously Variable Transmission," *Machine Tool and Hydraulics*, vol. 37, no. 5, pp. 170–174, 2009.

[13] G. Wang, S. Zhu, L. Shi, X. Ni, W. Ruan, and D. Ouyang, "Simulation and experiment on efficiency characteristics of hydraulic mechanical continuously variable transmission for tractor," *Transactions of the Chinese Society of Agricultural Engineering*, vol. 29, no. 15, pp. 42–48, 2013.

[14] M. Zhang, Q. Wang, D. Bai, Y. Yin, and X. Hao, "Speed changing law of hydro-mechanical CVT based on maximum efficiency of tractors," *Transactions of the Chinese Society of Agricultural Engineering*, vol. 32, no. 21, pp. 74–78, 2016.

[15] M. Zhang, *Control Strategy Development for Multi-Range Hydro-Mechanical Continuously Variable Transmission in Tractors*, Xi'an University of Technology, Xi'an, China, 2007.

[16] L. Xu, Z. Zhou, M. Zhang, and Y. Li, "Characteristics analysis of hydro-mechanical continuously variable transmission of tractor," *Journal of China Agricultural University*, vol. 11, no. 5, pp. 70–74, 2006.

[17] L. Xu, *Study on Characteristics of Hydro-Mechanical Continuously Variable Transmission of Tractor*, Xi'an University of Technology, Xi'an, China, 2007.

[18] B. Liu, S. Yuan, and X. Guo, "Parametric optimization based on the study of hydro- mechanical continuoulsy variable transmission of arithmetic type," *Journal of Mechanical Transmission*, vol. 30, no. 6, pp. 47-48, 2006.

[19] Z. Xue, "Modeling and simulation of hydro-mechanical continuously variable transmission based on simscape," *Tractor and Farm Transporter*, vol. 44, no. 2, pp. 12–16, 2017.

[20] Z. Tsonev, D. Yordanov, A. Dimitrov, and P. Petkov, "Estimation of measurement uncertainty for the determination of the total sulfur content in petroleum and petroleum products in UV-fluorescent analysis," *Petroleum & Coal*, vol. 54, no. 1, pp. 14–23, 2012.

[21] Y. Lin, L. Zhao, and C. Xiao, "An evaluation of the uncertainty of the submersible motor-pump efficiency measurement," *China Rural Water and Hydropower*, no. 3, pp. 116–119, 2018.

[22] H. Yu, T. Zhang, Z. Ma, and R. Wang, "Torsional vibration analysis of planetary hybrid electric vehicle driveline," *Transactions of the Chinese Society of Agricultural Engineering*, vol. 29, no. 15, pp. 57–64, 2013.

[23] J. Du, S. Yuan, C. Wei, and Y. Zou, "Performance analysis of dual mode hydro-mechanical transmission," *Transactions of the Chinese Society of Agricultural Engineering*, vol. 25, no. 4, pp. 86–90, 2009.

[24] C. Wei, J. Hu, C. Jing, and W. Wu, "Reasearch of engine speed governing rule based on the speed ratio follow-up control of hydro-mechanical transmission," *Transactions of Beijing Institute of Technology*, vol. 32, no. 5, pp. 455–459, 2012.

[25] Z. Guo, S. Yuan, C. Jing, and C. Wei, "Modeling and simulation of shifting process in hydraulic machinery stepless transmission based on AMESim," *Transactions of the Chinese Society of Agricultural Engineering*, vol. 25, no. 10, pp. 86–91, 2009.

[26] Z. Cheng, Z. Lu, J. Gong, and X. Diao, "Transfer function of steering system and acquisition method of ideal steering ratio," *Journal of Zhejiang University*, vol. 50, no. 7, pp. 1276–1283, 2016.

[27] A. Dermoune, D. Ounaissi, and N. Rahmania, "Oscillation of metropolis–hastings and simulated annealing algorithms around LASSO estimator," *Mathematics and Computers in Simulation*, vol. 135, pp. 39–50, 2017.

[28] W. Zhu, G. Chen, Z. Zhu et al., "Year prediction of a mild aroma Chinese liquors based on fluorescence spectra and simulated annealing algorithm," *Measurement*, vol. 97, pp. 156–164, 2016.

[29] Z. Cheng and Z. Lu, "Nonlinear research and efficient parameter identification of Magic Formula tire model," *Mathematical Problems in Engineering*, vol. 2017, Article ID 6924506, 9 pages, 2017.

[30] X. Lei, Q. Meng, W. Ma, and K. Yang, "Research on Transmission Errors of Closed Loop Gear Transmission Systems," *China Mechanical Engineering*, vol. 28, no. 6, pp. 675–682, 2017.

[31] X. Deng, A. Xu, J. Zhang, J. Li, and K. Xu, "Analysis and experimental research on the gear transmission error based on pulse time spectrum," *Journal of Mechanical Engineering*, vol. 50, no. 1, pp. 85–90, 2014.

[32] Z. Cheng and Z. Lu, "A novel efficient feature dimensionality reduction method and its application in engineering," *Complexity*, vol. 2018, Article ID 2879640, 14 pages, 2018.

[33] A.-h. Halassi, "An attractor-based multiobjective particle swarm optimization," *International Journal of Applied and Computational Mathematics*, vol. 3, no. 2, pp. 1019–1036, 2017.

[34] Z. Cheng and Z. Lu, "Semi-empirical model for elastic tyre trafficability and methods for the rapid determination of its related parameters," *Biosystems Engineering*, vol. 174, pp. 204–218, 2018.