

Development and evaluation of power consumption model for no-till planter based on working parameters

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Abstract: In order to fully understand the relationships of power consumption of no-till planter among tractor, soil properties and working parameters which affect the field operation, the power consumption model for no-till planter applied to overcome the coupling difficulties was developed in the study. Based on operation depth of no-till planter and soil properties as constraints in accordance with a certain distribution, the relationship data among traction force, forward speed and power output shaft by field test were collected and analyzed. The results showed that the relationship between traction power and power-take-off (PTO) power was negatively correlated. Under the same power consumption condition, the relationship between traction force and the PTO torque was linearly correlated, and the slope was basically consistent. Different power consumptions corresponded to different intercepts. When the forward speed was 6-7 km/h and PTO shaft rotational speed was 370-450 r/min, lower power consumption with higher working efficiency can be achieved. There was a direct correlation between total power consumption and the square of rotational speed multiplied by forward speed. The maximum correlation coefficient was found around 0.82. The findings set up a foundation for designing control system of no-till planter.

Keywords: no-till planter, power consumption, models, working parameters, evaluation

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1 Introduction

No-till planter is a key machine of conservation tillage. There is a great relationship among the power required in the work and its chop devices, opener, soil

properties, straw mulching etc. In order to study the relationship among the above parameters, the relationship among the type of ditching parts, working depth and soil types were experimentally investigated^[1,2]. The relationship between the parameters of operating speed and traction resistance was studied and the relationship models of each parameter were developed^[3,4]. Finite element (FE) models were established to simulate the soil cutting process and the force^[5-7]. The torques of rotary cutting soils and the power consumption and fuel consumption model of farming machinery under different operating parameters were studied^[8-11]. The vibration problem of rotary cutting parts during working was studied, which proved that the excitation of the machine or self-excitation vibration of the machine had a certain effect on the working quality and power consumption^[12-14]. Furthermore, the relationship between seeding quality and operating parameters was studied^[15-17].

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No-till planter was subject to the direct forces from tractor and soil in the field operation. There were some complex interaction relationships among operation parameters, tractor output parameters, soil surface conditions and operation quality etc. The function relations between some parameters caused by the coupling effect were known as implicit functions. This coupling relationship led to the fact that the study results obtained from the specific components were difficult to transplant applications. For the specific user of the machine, the purchased machine was often used for the seeding operation of a limited number of crops in the fixed plot. This indicated that the soil type of the machine operation was almost the same, and the depth of farming was the same as well.

For the above problems, the parameters such as operation depth and soil properties were taken as constants in accordance with some certain distribution characteristics, and the feedback interaction problem between no-till planter and the soil spatial heterogeneous characteristics and displacement delay feedback was analyzed. In this method, the interaction relationship among machines, different soil parameters and soil surface conditions were regarded as a black box to study its entirety input and output. We collected the data such as traction force, forward speed and PTO shaft parameters, etc. at the three-point hitch, and we studied the relationship between power consumption and traction, forward speed and PTO shaft parameters, which provided a basis for the design of parameter control system of no-tillage planter.

1 Interaction model of working parameters

1.1 Dynamics analysis

In the working process, the tractor achieved working feed through go-forward hanging node, and achieved operational requirements through PTO shaft driving working parts and all working parts of the machine operating in the soil. Analysis methods of the existing study can be summarized as the following aspects: Operational parameters or no-till planter parameters were analyzed and optimized by setting independent variables (such as the tractor working speed, PTO shaft rotational

speed, working depth, soil parameters and other factors) and the dependent variables (such as working efficiency, fuel consumption, working quality and other factors). The tractors, no-till planter and soil were studied as monomers in this method. However, due to soil parameters such as soil type, moisture, firmness and other factors are were the same, which affected on tractors and no-till planter differently. Therefore, it was difficult to find a theoretical method or testing relational models between working quality parameters and operating parameters. In addition, the interaction incentives between the no-till planter and the mulch on soil surface made no-till planter produce a certain frequency of vibration^[18,19]. This vibration transmitted to the tractor through the three-point hitch of the tractor, and got a larger response, which will react on the seeding and inevitably affect the quality of work^[19,20].

Under the ideal condition, working process of the no-till planter can be seen as a rigid body motion on the soil surface driven by tractor.

Since the cutting resistance led to a certain amount of elastically deformation in the soil cutting components, the stable working conditions were achieved by the balance between the elastic restoring force of the soil cutting components and the cutting resistance of the soil. The kinematic equations are shown as:

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = F(t) \tag{1}$$

$$k = P_0/x \tag{2}$$

where, x is the displacement on soil, m; m is the mass of cutting components, kg; c is the damping coefficient of cutting damper, N·s/m; k is the stiffness of the no-till planter, N/m; P_0 is soil cutting resistance, N.

In reality, since soil parameters, surface flatness and floor coverings always distribute randomly, the dynamic process between machine and soil tends to appear the following two cases of excitation situation.

The first case is: when ditching components encounter the hard soil, the depth of the ditching feedback block to ditching components is shown in Figure 1.

The ditching components are displaced a small distance ds from its equilibrium position because of interference. A greater tillage depth will lead to an increase of soil cutting resistance dP . The change of

displacement on soil is dx . According to Hooke's law, the changes of soil cutting resistance produce additional rigidity of the ditching components k' (N/m):

$$k' = dP/dx \tag{3}$$

And then, the real-time stiffness is expressed as:

$$k - k' = k - dP/dx \tag{4}$$

Thus, the kinematic equations are transformed into:

$$m\ddot{x}(t) + c\dot{x}(t) + (k - dP/dx)x(t) = F(t) \tag{5}$$

When ds decreases with dx increase, the ditching components become stable progressively. However, when ds increases with dx increase, dP increases with ds increase. So, stiffness expression is transformed into:

$$(k - k') < 0 \tag{6}$$

This case leads stiffness of no-till planter to an equivalent negative stiffness^[21,22], and ditching depth gradually deviates from the set depth over time.

The second case is: feedback block of time delay between the rotary component and soil (Figure 2).

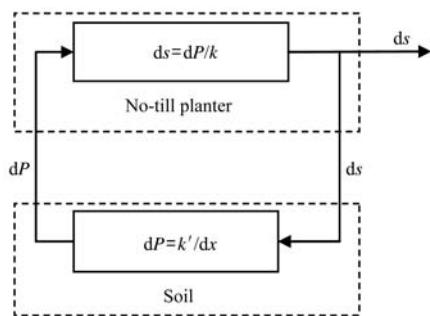


Figure 1 Feedback block of ditching depth

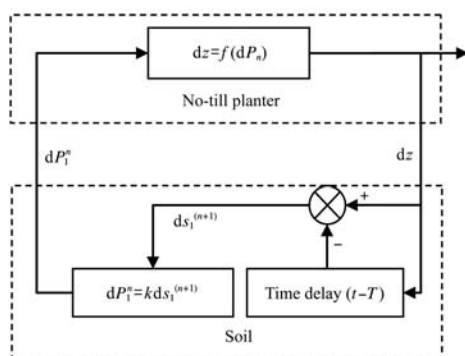


Figure 2 Feedback block of time delay

The movement of the rotary blade is synthesized by the rotation of rotary shaft and the forward movement along the tractor direction. Under stable operation condition, this study assumes that s_1 (m) is the cutting depth of each blade, P_1 (N) is the cutting resistance of each knife. When the rotary blade contacts hard soil during the rotation, the blade is subject to instantaneous

cutting resistance increase dP_1 . The resistance incremental affecting on no-till planter is bound to produce a vibration dz . After the blade rotating a certain time T (h), the next following blade will contact with the soil and lead to a cutting depth incremental s_1^1 . The cutting depth incremental affecting on machines will generate a cutting resistance incremental dP_1^1 . So there is the cycle and thus we get dP_1^2, dP_1^3, \dots

Since the force at time t (h) is determined by the vibration at moment $(t-T)$, the kinematic equations are expressed as:

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = F(t-T) \tag{7}$$

This motion process is either stable or diverging. The vibration of no-till planter will gradually increase in the case of $dP_1 \leq dP_1^1 \leq dP_1^2$, otherwise the system tends to be stable.

1.2 Modeling

The above analysis showed that the excitation and interaction of each parameter increases the difficulty of research. In response to this challenge, this study established a new model (shown in Figure 3) on the basis of studying tractor output, operational parameters and the working quality. In this model, the interaction relationship of machines, different soil parameters and soil surface conditions were regarded as a black box. And then, the dynamic parameters between the tractor and the black box were set as the research object. For the modeling, a test system consisting of multi-stage transmission, six-component force and torque acquisition system, speed sensor and other devices was used to collect the component force in all directions \vec{F}_i (N), the torque of PTO shaft M'_t (N·m), PTO shaft rotational speed ω_t (r/min), and forward speed v (km/h) in the time domain at three-point hitch location^[23].

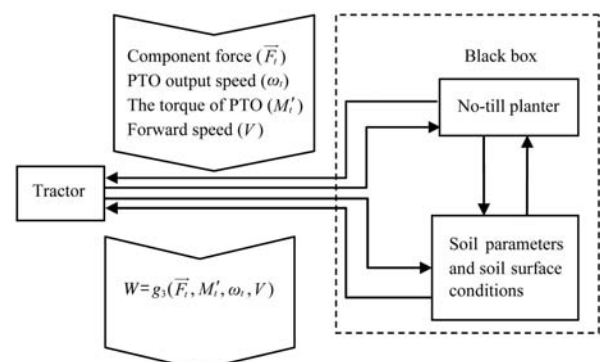


Figure 3 System block of model

For no-till planter, the component force and the torque of PTO shaft subjected at three-point hitch were mainly decided by its mass, center of mass location, forward speed and soil reaction force. For these parameters, the mass and mass centroid position was known as constant values, and the force which machinery affected on soil was equal to the reaction force value of the soil. Therefore, the main tillage planter force on the soil was decided by the PTO shaft torque M'_t , PTO shaft rotational speed ω_t , the tractor forward speed v .

Force vector values \vec{F}_t are expressed as a function including the following parameters:

$$\vec{F}_t = g_1(M'_t, \omega_t, v) \tag{8}$$

In the component forces, the lateral forces and the force in direction of gravity did not work. Referring to the damping expression, the relationship between traction force in forward direction F_x and forward speed v are expressed as the following:

$$F_x = b_0 + b_1 v^2 \tag{9}$$

where, b_0 and b_1 are the constant value to be determined.

Based on the power calculation formula, the real-time traction power (W_1) is shown as:

$$W_1 = F_x v = b_0 v + b_1 v^3 \tag{10}$$

For the no-till planter works in the same land and similar working content, factors which affected on the power consumption including soil parameters, tillage depth, mulch and other changes can be approximately regarded as a constant changing within a certain range.

For the rotary power, test showed that the power consumption was affected by the rotary speed ratio λ ^[24], which is expressed as:

$$\lambda = \frac{R\omega_t}{v} \tag{11}$$

where, R is the rotor radius, m.

The Equation (11) showed that, when the factors including soil parameters, operating depth, mulch, etc. were constants, the rotary power consumption (W_2) had some relationship with PTO shaft rotational speed ω_t and forward speed v . If the soil parameters were set to constants, and on the basis of the power prediction empirical formula in the literatures^[24-26], the rotary tillage power should be:

$$W_2 = b_2 v (b_3 + b_3 \omega_t^2) \tag{12}$$

where, b_2 and b_3 are the constant value to be determined.

Simultaneous Equations (10) and (12), the total power consumption model of no-till planter (W) is expressed as:

$$W = (b_0 + b_2 b_3) v + b_1 v^3 + b_2 b_3 v \omega_t^2 \tag{13}$$

2 Materials and methods

2.1 Experiment conditions

The tillage experiments were carried out in Laishui County, Hebei Province. The size of test field was a flat land about 350 m×50 m, soil texture was sandy loam, and the altitude was 46 m. Working temperature was 18°C. Surface roughness before treating was soil without conducting after harvesting corns. The surface of soil was covered with numerous straws (the coverage amount was about 1.2 kg/m²). The moisture content of soil was about 15%-20%.

Test equipment was composed of tractors, field testing platform and 2BMSF-12/6 type no-till Planter. A 66 kW tractor (Calibration traction force 21.3 kN, PTO power 56.3 kW, PTO shaft rotational speed 540 r/min) was used to towing field testing platform and no-till Planter. The tractor type was LOVOL EUROPARD TD904 wheeled tractor. Calibration traction force was 21.3 kN, engine calibration power was 66.2 kW, calibration rotational speed was 2300 r/min, maximum torque/rotational speed was ≥315 N·m/1500-1700 r/min. Field test platform was equipped with a transmission, which can regulate the PTO shaft rotational speed range from 0 to 1000 r/min with a total of 16 stalls.

The basic parameters of 2BMSF-12/6 no-till planter were: static weight 780 kg, supporting power 44.1-58.8 kW, sowing wheat with 12 rows, fertilizing wheat with 6 rows, work efficiency 0.6-0.73 hm²/h. The tillage depths for rotary cultivator were 10 cm, rotary width 2.2 m.

2.2 Test content and method

This study conducted the field test consisting of tractor, field test platform and 2BMSF-12/6 no-till planter under the conditions of different forward speed and PTO shaft rotational speed of the transmission gear. The forward speed was set to 2-10 km/h, the PTO shaft output was set to 200-700 r/min. In order to make the power consumption equivalent to the power consumption under the same operating area, the data was collected by the

same distance. The minimum sampling frequency of the sensor was set to 0.1 m. Test area was composed of a stable area, measuring area and parking area. The size of measuring area was 400 m for the tests. The length of stabilizing zone was 5 m located in front of the measuring area. Parking area was located behind the test area, shown with the mark.

3 Test results and analysis

3.1 Test results

The test results including forward speed, no-till planter traction force in the forward direction, PTO shaft rotational speed and PTO torque were shown in Figure 4. The following conclusions can be obtained from Figure 4: (1) Under the premise of increasing forward speed slowly, traction force of no-till planter in the forward direction and the PTO torque did not change significantly. (2) When the forward speed was 3 km/h, PTO shaft rotational speed was 300 r/min, the traction force in the forward direction and PTO torque required for the operation reached the minimum. (3) It can be obtained by studying the traction force peaks in Figure 4 that under the premise of no significant change in

forward speed, PTO torque can be reduced by increasing the PTO shaft rotational speed, but it will result in a huge increasing in traction force.

Traction power, PTO power and total power consumptions of no-till planter were shown in Figure 5. It can be seen from the comparison of three power dissipation that improving working efficiency (forward speed) did not lead to power increase absolutely. Interactions of traction force, PTO torque and PTO shaft rotational speed affected power dissipation greatly. Figure 5 showed that, when the forward speed was 2.5-3 km/h and PTO shaft rotational speed was 200-300 r/min, the total power consumption reached the minimum, but due to the low forward speed, the working efficiency was lower. Comparing the traction power and PTO power in 100-250 m section and 300-400 m section, the relationship between traction power and PTO power was negative correlation. The data analysis of Figures 4 and 5 showed, under the premise of no significant change in PTO shaft rotational speed; the interaction effects between traction power and PTO power significantly were significant.

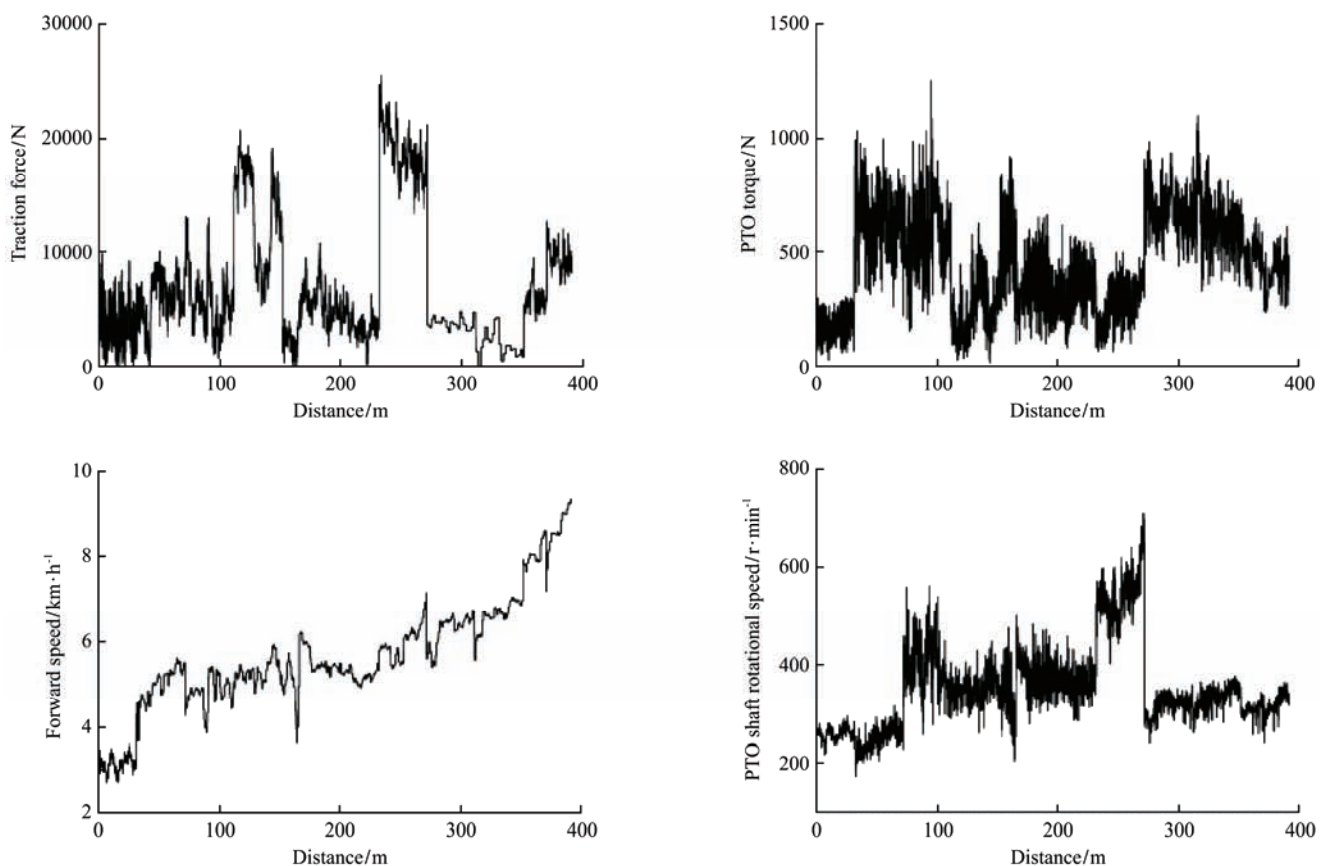


Figure 4 Test results of no-till planter

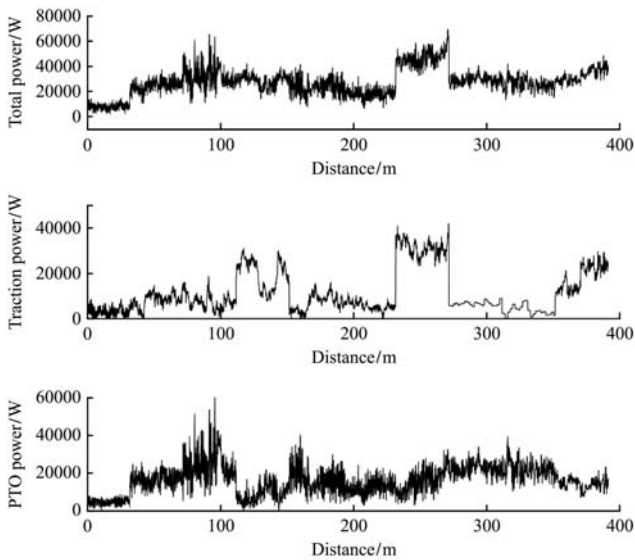


Figure 5 Power consumption of no-till planter

3.2 Power response to working parameters

Setting the forward speed and PTO shaft rotational speed as the tractor output parameters, the total power consumption response surface contours of no-till planter was shown in Figure 6. The blue area to the red area represented the total power from Min to Max. The rectangular box in Figure was the stable changing area of the power. In this area, the forward speed was linearly related to the output shaft speed in the same power zone. Blue area in Figure 6 showed that, when the forward speed was 6-7 km/h and PTO shaft rotational speed was 370-450 r/min, we will get the lower power consumption with higher working efficiency.

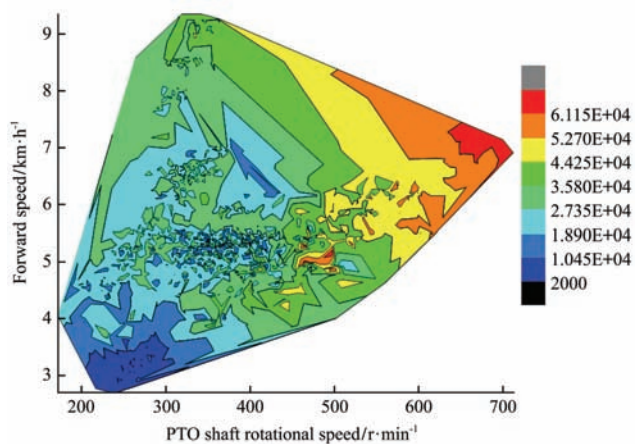


Figure 6 Power response surface to tractor output

Setting the traction force and PTO torque as the no-till Planter feedback parameters to tractor, the total power consumption contours of no-till Planter was shown in Figure 7. Different colors contours in the figure showed, under the same power consumption condition,

the relationship of traction force and the PTO torque was not only linearly related, but also the slope was basically consistent. Different power consumption corresponded to different intercept.

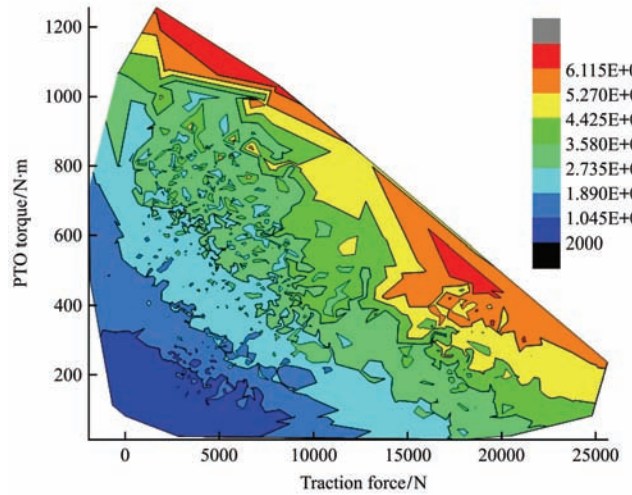


Figure 7 Power response surface to no-till planter feedback

The total power consumption contours of the PTO shaft speed and torque were shown in Figure 8. It showed that under the conditions of no violent fluctuations between the traction force and forward speed, the total power consumption was mainly decided by the PTO shaft rotation speed and torque. The higher the PTO shaft rotation speed was, the higher the total power consumption was.

3.3 Prediction models of total power consumption

Regressions analysis was performed on the total power consumption using sample data in Figure 6. The regression coefficients were obtained based on Equation (13). In regression analysis model, the total power consumption was set as the response variable, and variables $v, v^3, \omega_t, v\omega_t^2$ were set as independent variables. According to the modeling of the least square method and sample data, a number of possible multiple linear regression model were established between independent variables and the dependent variable:

$$y_1 = b_4v^3 + b_5(v\omega_t^2) + b_6v + b_7\omega_t + b_8 \quad (14)$$

$$y_2 = b_4v^3 + b_5(v\omega_t^2) + b_6v + b_8 \quad (15)$$

$$y_3 = b_4v^3 + b_5(v\omega_t^2) + b_7\omega_t + b_8 \quad (16)$$

$$y_4 = b_4v^3 + b_5(v\omega_t^2) + b_8 \quad (17)$$

$$y_5 = b_6v + b_7\omega_t + b_8 \quad (18)$$

where, b_4-b_8 are constant values to be determined

In order to evaluate the effects of above regression models, coefficient of determination R^2 was set as the model fitting test indicator for comparison. Coefficient of determination, also known as the goodness of fit R-Square, referred to the regression level to the sample data, which reflected the degree of influence between independent variables and dependent variables. Adjustment R^2 (Adj. R^2) eliminated the influence of the variables number to the model, so it can be used as the test criteria to compare models. Table 1 presented a summary of Adj. R^2 for each regression models.

Table 1 Adjustment R^2 for each regression models

Evaluation Index	y_1	y_2	y_3	y_4	y_5
Adj. R^2	0.718	0.719	0.683	0.675	0.669

Range of Adj. R^2 values was from 0 to 1. When Adj. R^2 was closing to 1, better regression model achieved better results. As can be seen from Table 1, y_2 was the best regression result. By comparing y_2 with y_1 , Adj. R^2 values were slightly different. However, y_1 had one more independent variable ω_t than y_2 . This indicated that ω_t had linear relationship with another variable in the regression equation. Therefore, to avoid multicollinearity, the total power consumption model for the forward speed and PTO shaft rotational speed was described by the following regression equations:

$$W = 101.58v^3 + 0.0146(v\omega_t^2) - 15770.07v + 91734.71 \quad (19)$$

The F value of the model was 1375 in F -test, so, this regression equation was highly significant at the level of $\alpha=0.01$.

In order to reject variables those who had no significant effects to the regression model, the statistically significant of each independent variables were judged by using significance test (t -test). The t -test results were shown in Table 2, which showed that the estimated parameters were significant to the model, and the independent variable $v\omega_t^2$ was highly significant.

Table 2 T -test of each variable

	Value	Standard error	t -value	Prob> t
Intercept	91734.71	4667.38919	19.6544	0
$v\omega_t^2$	0.0146	2.49993E-4	58.39161	0
v^3	101.58	6.02812	16.85156	0
v	-15 770.07	972.00425	-16.22429	0

Because there were multiple variables in regression model, the variables may be associated with each other.

It was necessary to analyze each variable by using Pearson correlation analysis. The correlation analysis results were shown in Table 3.

Table 3 Correlation coefficients of indicators

	Total power consumption	$v\omega_t^2$	v^3	v
Total power consumption	1	0.81732	-0.05681	-0.10307
$v\omega_t^2$	0.81732	1	-0.16141	-0.18222
v^3	-0.05681	-0.16141	1	-0.99093
v	-0.10307	-0.18222	-0.99093	1

Table 3 showed that it was a positive correlation between the total power consumption and variable $v\omega_t^2$, and reached a correlation coefficient maximum of 0.81732. This meant that there was a direct correlation between total power consumption and $v\omega_t^2$. There was a negative correlation between total power consumption and forward speed v and v^3 , which was considered less correlation. The independent variable $v\omega_t^2$ had a low correlation with the other independent variables.

4 Conclusions

On the basis of this study, the following conclusions can be drawn.

1) In the conditions that the forward speed did not change significantly, increasing PTO shaft will reduce the PTO torque, but it will lead to the significant increase of the tractor power. In the conditions that the PTO shaft rotation speed was stable and changed slightly, the interaction between tractor power and PTO shaft power was significant. Therefore, there was a negative correlation between the tractor power and the PTO shaft power.

2) The forward speed was linearly related to the PTO shaft speed in the same power zone. When the forward speed was 6-7 km/h and PTO shaft rotational speed was 370-450 r/min, we will get the lower power consumption with higher working efficiency.

3) In the conditions of no violent fluctuations between the traction force and forward speed, the total power consumption was mainly decided by the PTO shaft rotation speed and torque. The higher the PTO shaft rotation speed was, the higher the total power consumption was. The effect of multiplying the speed and the square of PTO shaft rotation speed on the total power was the most significant.

Acknowledgments

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